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Entrainment and Deposition Studies in Two-Phase Cross Flow: Comparison Between Air-Water and Steam-Water in a Square Horizontal Duct

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Prepared for
U.S. Nuclear Regulatory
Commission

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ABSTRACT

Air-water simulation studies of two phase steam water flow relevant to the upper plenum of a PWR during reflood situations have recently been undertaken at Harwell for the US Nuclear Regulatory Commission [1]. In order to give confidence that the simulation fluids were capable of modelling the important features of the flow in the actual system, a relatively basic comparison experiment has been carried out.

Water entrainment and deposition tests have been carried out on a pair of 2.5 cm diameter vertical rods mounted in a cross flow of steam or air in a 10.2 cm x 10.2 cm tunnel.

Water was added to the system either through sinters positioned in the top of the test rods or through upstream sprays mounted in the floor of the duct.

The pressure of the system was close to atmospheric and the steam used was slightly superheated. The water could be injected hot or cold but the air was always at near ambient temperature.

The air and steam systems exhibited similar characteristics to one another. A 'critical' film flowrate was identified for the rods which, once reached, either by injection through the sinters or by entrainment from the main two phase stream, was not exceeded with further water addition.

The 'critical' film flowrate decreased with increase of cross flow velocity and was lower for air than steam at the same velocity.

Some scatter was evident in the results, some of which could be associated with wetting phenomena which was clearly identified in the case of the air-cold water tests.

The results from the air and steam tests were found to be reasonably well correlated on the basis of the cross flow momentum flux of the air or steam.

More detailed comparison of the two systems awaits the formulation of a suitable physical model but in the meantime the results of the present study do give more confidence than hitherto that air-water can be used to model important features of cross flow in steam-water systems.

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1. INTRODUCTION

Two-phase flow studies relevant to the upper plenum of a PWR during reflood situations have recently been undertaken at A.E.R.E. Harwell under contract to the US NRC [1]. It was agreed with the NRC that in order to reduce cost and rig construction time the fluids to be used for the simulation of the real steam-water system would be air and water. Further tests were also planned [2] in which air-water simulation would again be used.

Even when simulating essentially adiabatic systems there are some significant differences in the relevant physical properties between atmospheric pressure air and cold water and steam and water at 100°C.

Table 1 shows that the most significant differences lie in the air and steam densities and the dynamic viscosity of the water.

Correlation methods and theoretical treatments have been developed for axial two phase flow [3,4,5] which enable rigorous comparison between different fluid systems to be done. It is widely agreed that air-water mixtures can be used to simulate adiabatic steam-water axial flow systems and the results used quantitiatively provided the developed scaling laws are used to relate the two sets of fluids.

Because of the relative simplicity of using air-water, which results in cheaper and quicker studies, there is incentive to examine its use in the simulation of more complex flow situations.

To give confidence that the cross flow air-water simulation tests relevant to the PWR upper plenum can be related to steam-water, a simple comparison experiment in cross flow has been undertaken. This report describes the study and discusses the results.

2. DESCRIPTION OF TEST TUNNEL USED

Since it was not intended that the results of the tests would necessarily be directly applicable to a particular flow situation or location in the PWR upper plenum, the scale of the experiment was kept small. The required maximum cross flow velocity of about 17 m/s combined

with a readily available mains steam supply dictated a maximum duct cross sectional area of 0.01 m^2. A duct of square cross section (10 cm x 10 cm) was chosen and in this were positioned two 2.5 cm diameter full rods and two half rods (on the wall) in the manner shown in Figure 1a. Provision was made to supply heated water to the top of the rods via a porous sinter and upstream of the rods via an adjustable spray pipe (see Figure 2a) in the floor of the tunnel. Water which was captured by the rods from the upstream spray or the fraction of the injected sinter flow which remained on the rods was measured by catching the falling film in annular slots at the base of each rod. The arrangement of the system is shown in Figure 1b.

The steam and air supply for the tests was taken from the site supply and was piped to the square duct, via a pressure reducing valve, through a 38 mm diameter round pipe some 2 m long. An orifice plate was located in the pipe to allow mass flow measurements to be made. A round to square smooth transition was fitted 0.5 m downstream of the orifice plate.

The superheat resulting from the blow-down to near atmospheric pressure of the site steam (nominally close to saturation at 5.5 bar) could be controlled when required by a simple spray de-superheater (Figure 2b) located some 2.0 m upstream of the test section.

A further upstream spray system consisting of a rotatable set of 21 x 1 mm holes was located in the base of the tunnel some 0.75 m upstream of the first test rod (see Figure 2a).

The main flow from the rig was rejected directly to atmosphere so that the test section pressure was nominally atmospheric for all tests. A traversable pitot static probe was mounted in the duct upstream of the test rods. Viewing ports were provided on either side of the section containing the rods. The walls of the tunnel were provided with externally wound electrical surface heaters and the whole tunnel was lagged.

A schematic layout of the system is shown in Figure 3.

3. EXPERIMENTAL PROCEDURE

3.1 Air Tests

Having established during rig commissioning the setting of the pressure reducing valve which permitted the maximum required air flow to be obtained, subsequent flow control was achieved by setting the main control valve to the required opening. The normal procedure adopted for the tests was to set the required air flow and use a range of water injection rates at that flow.

Water flow to the upstream spray or the rod sinter injector was measured with calibrated variable area flow meters. Water collected from the rods was measured by diverting the flow in the catchment gutters to calibrated cylinders. Evaporation occurred during this procedure but the amount was estimated to be insignificant.

Only ambient temperature air was used but a range of tests was carried out with heated water to test the effect of liquid film and droplet physical property changes.

In addition to the orifice plate air flow measurement, a velocity profile was taken upstream of the test rods. These data plus an exhaust anemometer measurement served as a calibration check on the orifice plate which was mounted in a non-standard (38 mm diameter) pipe.

Direct observation of the water droplets downstream of the test rods was possible provided a small purge of air was passed down the window mounting tube. This prevented water droplets entering the side tubes. A further safeguard to reduce splashing was a nylon mesh lining placed on the inside wall of the tube.

During commissioning it was found that unfortunately the brazing procedure adopted for mounting the sinters into the test rods had caused blocking of the flow channels. Although this was quickly rectified for the main rods it was not possible without major changes to clear the half rods. Thus no injection flow has been used on the half rods mounted on the wall.

3.2 Steam Tests

The procedure for the steam tests was similar to that used for the air.

Ideally the steam and injected water temperatures were required to both be at the saturation temperature ($\sim 100°C$). However the water injection method of reducing the steam superheat can, if full spray evaporation is not achieved, lead to additional unknown amounts of water reaching the rods.

In the majority of tests therefore the steam was allowed to remain slightly superheated. Steam flow rate was measured with an orifice plate. A check on the accuracy of this method was obtained from the air tests (see 3.1) by pitot static traverse of the duct upstream of the rods and by vane anemometer at the exhaust from the rig. Attempts were made at direct pitot static traverses in the steam but problems with condensation in the lines to the gauge prevented stable readings being obtained. However, the geometry of the system upstream of the pressure relief valve was identical in both the steam and the air tests and thus no change of velocity profile would be expected when changing from steam to air and vice-versa.

Direct observation of the water droplets downstream of the rods in the steam was attempted by keeping the observation windows hot. The interspace between the double glazed viewing ports were purged with hot air. However, this did not entirely prevent condensation on the inner window so the air bleed technique described in 3.1 was successfully adopted.

4. RESULTS AND DISCUSSION

4.1 Entrainment Tests in Air

The water collected from rods 1 and 4 (see Figure 1) as a function of that injected through the sinter for a range of cross flow air velocity+ is given in Figures 4 and 5. It can be seen that both sets of results are similar in character to each other and to previously observed results obtained in the earlier programme of air-water tests [1]. Up to a given

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+ Note. All cross flow velocities referred to are superficial values, i.e. volumetric flowrate divided by full duct cross-sectional area.

injected water flowrate, the level depending on the cross flow essentially all the water remains on the rod. Beyond this so called 'critical flowrate', any additional water injected onto the rod is mostly entrained by the air stream. As in the earlier tests, some scatter and modification to the idealised behaviour (see Figure 5.1, reference 1) may be noted. It also appears that, for a certain range of water flow, rod 4 is capable of supporting a higher water flowrate than the upstream rod (1). However, in addition to the directly injected water, rod 4 also receives some water by deposition of part of the entrained flow from rod 1. Rod 4 is also in the turbulence created by rod 1.

To clarify the relative behaviour of rod 4 with respect to water captured from rod 1 a set of runs was carried out with no flow injected through the sinter of rod 4. Also carried out during this series of runs was a check on any 'hysteresis' effect which could have perhaps accounted for the scatter of results seen. It was thought that once a rod had become fully wetted with a high water flow any subsequent low injected flow might result in a different adhering film than that produced during the initial injection. Measurements of entrainment were thus made during increasing sequences of injected flow and decreasing ones.

The results of both investigations are shown in Figures 6-9. The lowest cross flow of air used was 7 m/s since no significant entrainment occurred below this figure for any of the water injection rates used.

It will be noted that the water captured by rod 4 mirrors the entrainment from rod 1 once entrainment from the latter has started. The amounts captured by rod 4 are somewhat variable being typically around 10% of the water entrained from rod 1, at the lower air velocities, rising to about 25% at the highest air and water rates.

The behaviour of rod 4 compared with 1 is influenced by two effects. First it is in the wake of rod 1 and secondly it is fed by water being shed from the latter. Assuming that the deposition on rod 4 is similar when sinter injection is used on both rods comparison with Figures 4 and 5 gives some indication of the relevant importance of the two effects.

For the water and air flowrates below about 3 kg/min and 11 m/s respectively, rod 4 supports significantly more water film than rod 1, the

extra amount not being accountable for by the amount deposited from the upstream rod (1). The sheltering effect of rod 1 is thus the main influence on the water film supportable by rod 4 for this condition.

At high water and air flowrates the supportable water film on the rods is similar. Both rods are essentially fully saturated, any sheltering effect of rod 1 is relatively small and the water shed from the latter is about equal to the critical or saturated value for rod 4 which simply sheds the excess downstream.

The hysteresis effect is particularly noticeable at the lower cross flow air velocities. It will be noted from Figure 6 that the water collected from rod 1 after pre-wetting was, over one part of the injection range, more than double that collected before the rod had been saturated. The results were repeatable and in fact the phenomena was observed in the tests reported in [1].

As the velocity of the air was increased the hysteresis effect progressively disappeared, being essentially insignificant at a velocity of about 15 m/s.

During the air tests a tunnel velocity profile was carried out to ensure that the upstream injection systems were not causing any gross distortion to the air stream. A typical result is shown in Figure 10 which indicates that the upstream water injector pipe in the base of the tunnel only caused a small skewing of the velocity profile. The measurements also permitted a cross check calibration of the orifice plate mass flow calculations. Agreement between the two mass flows was within 5%.

4.1.1 Water Temperature Effects

In order to test the relative significance of differences caused by the use of cold water and air in simulating the saturated steam water cross flow system a series of runs was carried out with hot water. The input air stream was kept at ambient temperature but the water which was injected into the sinters of both rods 1 and 4 was heated to about 95°C.

The results are shown for a range of air velocities in Figures 11 and 12. It will be noted, by comparison with Figures 4 and 5, that in general

more water is collected for a given injected flow, in the hot runs than in the cold. This is particularly apparent for the intermediate air velocities of 7-11 m/s. The 'critical flowrates' are also higher in the hot water tests, again with the biggest increases being most easily distinguished for the intermediate range of air velocities.

The temperature increase was found to almost eliminate the hysteresis phenomena discussed above. This is clearly shown in Figures 13-16 which may be compared with the results from the earlier cold runs (Figures 6-9). It is important to note by comparing Figures 9 and 16 that the results for the high cross flow velocity is less effected in all respects by the changes in water temperature.

The most significant change in physical property brought about by raising the temperature of the water is the reduction in viscosity by a factor of about 3.5 (see Table 1). The corresponding reductions in surface tension and dersity are only 24% and 4% respectively. This decrease in viscosity will result in thinner films (for a given film flow rate) and this in turn would be expected to reduce the amount of entrainment. It must be appreciated though that the film thickness is relatively insensitive to viscosity so that the other fluid properties, although changing much less, may have equal significance. Furthermore, the disappearance of hysteresis at higher temperatures is difficult to explain in terms of viscosity changes and is perhaps due to the reduction of surface tension.

4.2 Deposition Tests in Air

Initial tests with the upstream water injector spray (Figure 2b) showed that the amount of water deposited on the rods was only weakly effected by the orientation of the spray. The subsequent deposition tests were thus all conducted with the central row of the three row hole array angled at 30° towards the test rods.

It was found that a considerable amount of the injected spray hit the walls of the duct.

For each cross flow air velocity the spray flow was progressively increased and the water deposited on each rod measured. The results for cold water are shown in Figures 17 and 18.

No measurable flow was collected from either rod until at least 1 kg/min of water spray flow was being injected into the air stream. At low air cross flow an even higher water flow of around 3 kg/min was necessary before net collection commenced.

There is some scatter on the results but in general once collection of water on either rod became measurable the collected flow increased approximately linearly with further increase of upstream water injection.

No clear progressive trend of collected amounts of water with increase of air velocity is apparent from Figures 17 and 18 although the highest amounts collected for each rod was for the intermediate velocity of 11.2 m/s. The amount of water collected from the downstream rod (4) was in general about half that from the leading rod (1) for corresponding conditions.

Because of the small amounts of water actually entering the main air stream the collected flow was, it would appear, always well below the critical amount where further deposition is re-entrained. It is thus felt that sinter injection tests are of greater value for the steam-water comparison than the upstream water injection tests. The deposition information comes more naturally from the examination of the behaviour of the downstream rod (4), with and without sinter injected water, as it intercepts the water which is shed from the leading rod.

However, to complete the tests a set of upstream injection runs, was done with hot (96°C) water.

4.2.1 Water Temperature Effects

A similar set of upstream water injection tests to those described above were carried out with water at about 96°C injected into the cold air stream. Although some cooling of the spray was inevitable, thermocouples in the system and collected water temperature indicated that the water hitting the rods was at least 70°C.

The results of the hot water tests are shown in Figures 19 and 20.

No dramatic effects of the water temperature increase are discernible.

A small reduction in collected flow is apparent for the downstream rod at the higher cross flows and the onset of measurable deposition starts somewhat earlier for the hot water.

4.3 Entrainment Tests in Steam

A similar set of tests to those described in 4.1 was carried out in slightly superheated steam at near atmospheric pressure. The water collected from the rods as a function of liquid injected through the sinters for several steam velocities is shown in Figures 21 and 22.

It will be noted that the results exhibit very similar characteristics to the cold water-air tests shown in Figures 4 and 5.

However, the absolute amount of water collected is different for a given cross flow velocity of steam compared with the same or closely similar velocity of air. In general the amounts of water collected in the steam case are higher and the critical rod flow for the commencement of entrainment is also raised.

There is some evidence that over part of the range tested the downstream rod (4) again, as in the air runs, supports more water flow than the first rod. The relative differences between the amounts collected for the two rods, however, is small.

To complete the comparison with the air tests a set of runs was carried out to check the hysteresis effect discussed in 4.2 and also to examine the deposition levels occurring on the downstream rod.

Shown in Figures 23-26 are plots of water collected vs. sinter injected water in which the amount of water injected on rod 1 only was progressively raised to the maximum, in increments, and then decreased to the minimum. Some hysteresis effect is discernible but in general it is relatively small being about the same as that seen during the hot water-air tests (see Figures 13-16).

As in the air tests discussed in 4.2, once entrainment from the front rod commences, then the liquid collected from the downstream rod mirrors the entrainment from the first rod. Over quite a wide range of conditions,

roughly 25% of the water shedding from the upstream rod is captured by the downstream rod. It is relevant to note that Richter et al [6] in their recent related studies on cross flow deposition from upstream sprays noted about 30% collection efficiency on 5 cm rods up to a cross flow superficial velocity of about 13 m/s (26 m/s local velocity). When saturation film flow on the downstream rod is reached the deposited amount should, by definition, remain roughly constant, excess liquid from upstream being re-entrained. This condition appeared to have been reached in the air runs (see Figures 9 and 16) but appeared initially to have not been quite achieved in the steam runs. The behaviour of the system at a steam flow of 21 m/s, which was expected to produce downstream rod saturation, was very similar in fact to that at a steam flow of 15 m/s (see Figures 25 and 26) with the maximum amount collected from rod 4 falling well below rod 1.

This result prompted a repeat of the 21 m/s condition in which the film flow was increased up to approximately 9 kg/min (previous maximum being 6 kg/min). The result of this test is shown in Figure 27 where it can be seen that the behaviour up to about 6 kg/min was the same as that observed previously (Figure 26). Also it would appear that, in spite of the amount of collected water on rod 4 remaining below rod 1, a saturated condition was essentially achieved. Very little further increase of collected water from rod 4 took place after about 5 kg/min was being injected onto rod 1.

The slightly lower saturation flow seen on rod 4 compared with rod 1, which was opposite to that noted for air at the highest velocity, may have been reversed to agree closer with the air if the steam velocity had been taken to a slightly higher value.

To complete the study at 21 m/s steam flow, a check was done on the water film supported by rod 4 when water was injected through the sinters of both rods. The result is shown in Figure 28 which indicates that for this velocity any sheltering or wake effects are minimal and the two rods support about the same film flow. It will be noted that the deposition saturation flow did not quite reach the level of the near saturation flow in the injection tests. However, this is not surprising in view of the fact that film flow conditions on and immediately adjacent to the sinter are somewhat artificial compared to other locations. This could well account for the differences noted between the deposition and entrainment levels of saturation on the downstream rod.

4.4 Deposition Tests in Steam

Tests similar to those described in 4.2, for air, were carried out in slightly superheated steam at near atmospheric pressure. The upstream water injector was fixed in the identical position to that used for the air tests. Water heated to saturation conditions was sprayed into the steam flow and the resulting deposition on the test rods examined.

The results for a range of conditions are shown in Figures 29 and 30. It can be seen that, as in the air tests, amounts of water collected were small relative to the injected flow with the onset of measurable collection not starting until about 1 kg/min was being injected. Again, as in the air tests, there is some scatter of results and a clear progression of collected flow with steam velocity is not apparent over the whole range. However, the results are very similar to those obtained in the air tests as can be seen by comparison with Figures 19 and 20. It will be noted that the steam velocities giving rise to these similar results are higher than in the air runs. Why this behaviour and that seen for the entrainment comparisons between air and steam might be expected, is discussed in Section 6 where a correlation method for the air and steam systems is suggested.

5. DROPLET SIZE MEASUREMENTS

A droplet size technique which is based on the scatter of a laser beam which is transmitted across the duct through the observation ports has been attempted. This has indicated that the mean water droplet size of the water shedding from the rods is larger than the present lens system will accommodate (1.0 mm). New lenses are to be fitted and the results presented in due course.

6. CORRELATION OF STEAM-WATER/AIR-WATER RESULTS

The main aim of the study undertaken on the tunnel was to demonstrate that air-water can be used to simulate quantitatively certain steam-water situations relevant to PWR upper plenum studies.

The size and layout of the rig was dictated mainly by considerations of economy, however the system does contain some of the important features necessary for such a comparison but there are only effectively two rods.

Also the rods were short and thus end effects could have had a significant influence on the behaviour of the system.

The upstream injection tests were, it is felt, so dominated by spray falling on the walls of the duct that critical comparison by any correlation technique would be of doubtful value.

The entrainment tests were less complicated by unwanted side effects and some forms of correlation should be possible for the two systems.

The preceeding sections have indicated that, at least qualitatively, the air-water/steam-water systems behave in a similar manner. The hysteresis effect seen over part of the range of cross flows in the cold water-air tests being the exception.

Unlike axial two phase flow there has been relatively little development of physically based models for two phase cross flow. Some discussion of the limited theories so far reported was given in AERE-G.1047 [1] and more recently by Richter et al [6].

It would be expected that the dominant forces on the rod film would be proportional to the momentum flux of the cross flow. The detailed behaviour of the film under the action of the cross flow will depend on the liquid density, viscosity and surface tension. It will be seen from Table 1 that the most significant differences in the relevant physical properties between atmospheric pressure saturated steam and water and cold air and water are the vapour and gas density and the viscosity of the water. The water surface tension and density are much less affected by the temperature differences.

As an initial correlation attempt the results obtained during the entrainment tests were re-plotted as a function of cross flow momentum flux of the air or steam flow.

Each rod flow was treated as an individual case for the air and steam systems and the liquid collected presented as a fraction of the liquid injected. For the cold water-air cases the collected film flowrate was taken as that messured during decreasing rates of injected flow.

The plots are shown in Figures 31-36 for rod 1 and Figure 37-43 for rod 4.

It will be noted that the general trend is the same for all three systems. The larger the injected film flow the smaller the momentum flux needed to induce the onset of entrainment and the more rapidly the entrainment increases with momentum flux. The trend towards an asymptotic value of film flow fraction is also rapidly approached with momentum flux increase in the case of large amounts of injected flow.

There is some scatter of the data but in view of the relative complexity of the flow situation and the difference in the water physical properties in the ambient air-water system there is clearly a large measure of agreement between the results for the three systems when correlated on a momentum flux basis.

Critical flowrate as a function of cross flow momentum was also examined. Allowances must be made for the difficulty in establishing precise values of critical flowrate. Even limiting the data to those found during decreasing sequences of injected water (to avoid hysteresis spread) there is an uncertainty of perhaps $\pm$ 30% present in the data. However, the plot of critical flowrate vs. momentum flux presented in Figure 43 shows the trend, and the measure of agreement between the three systems studied.

Clearly a more advanced correlation technique or physical model is required to enable a more rigorous comparison of the systems to be made. This will need to take into account the liquid physical property differences including the surface tension which probably accounts for such detailed differences as the hysteresis effect noted.

7. CONCLUSION

Water entrainment and deposition tests have been carried out on 2.5 cm diameter vertical rods mounted in tandem in a 10 cm square duct through which was passed, for comparison purposes, air or slightly superheated steam.

The majority of the data obtained came from tests in which water was added to the system through sinters mounted at the top of the rods and the

amount of water retained by the rods measured using a take-off gutter at the base.

The air and steam systems exhibited similar characteristics to each other. Once a particular sinter injected film flowrate was reached (termed 'critical') little further change of collected rod film occurred with further addition of water.

The 'critical' film flowrate decreased with increase in cross flow velocity and was lower for air than for steam at the same velocity.

Tests in air using cold water showed that, for velocities up to about 11 m/s, the collected film flowrate depended on whether the rod had previously been flooded with water. This 'hysteresis' effect was significantly reduced in air when the water was heated. The effect was also much less marked in the steam tests.

Droplet sizing measurements indicate that the mean droplet size a short distance downstream of the rods is at least 1.0 mm in both the air and steam cases studied. More detailed measurements still remain to be done.

A theoretical model for entrainment and deposition in two-phase cross flow is not presently available for a rigorous comparison between air and steam systems. However, the principle features of the entrainment and deposition behaviour in the two systems was found to be reasonably correlated on the basis of the cross flow momentum flux of the air or steam.

The results of the present study gives more confidence than hitherto in the use of air-water mixtures for modelling wet steam systems other than those commonly simulated, in which axial flow dominates.

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T A B L E 1

Relevant Physical Properties of Air, Steam and Water at a Pressure of 1.01 bar

Temp. °C	Air		Steam		Water		
	Density kg/m^3	Viscosity x 10^5 Ns/m^2	Density kg/m^3	Viscosity x 10^5 Ns/m^2	Density kg/m^3	Viscosity x 10^3 Ns/m^2	Surface Tension N/m
15	1.2	1.78			999	1.136	0.071
20	1.18	1.8			998	1.002	0.072
40	1.10	1.9			992	0.651	0.067
60	1.04	2.0			983	0.463	0.065
80	0.98	2.1			972	0.351	0.062
100	0.93	2.2	0.598	1.2	958	0.279	0.058
120	0.88	2.3	0.562	1.3	943	0.230	0.054

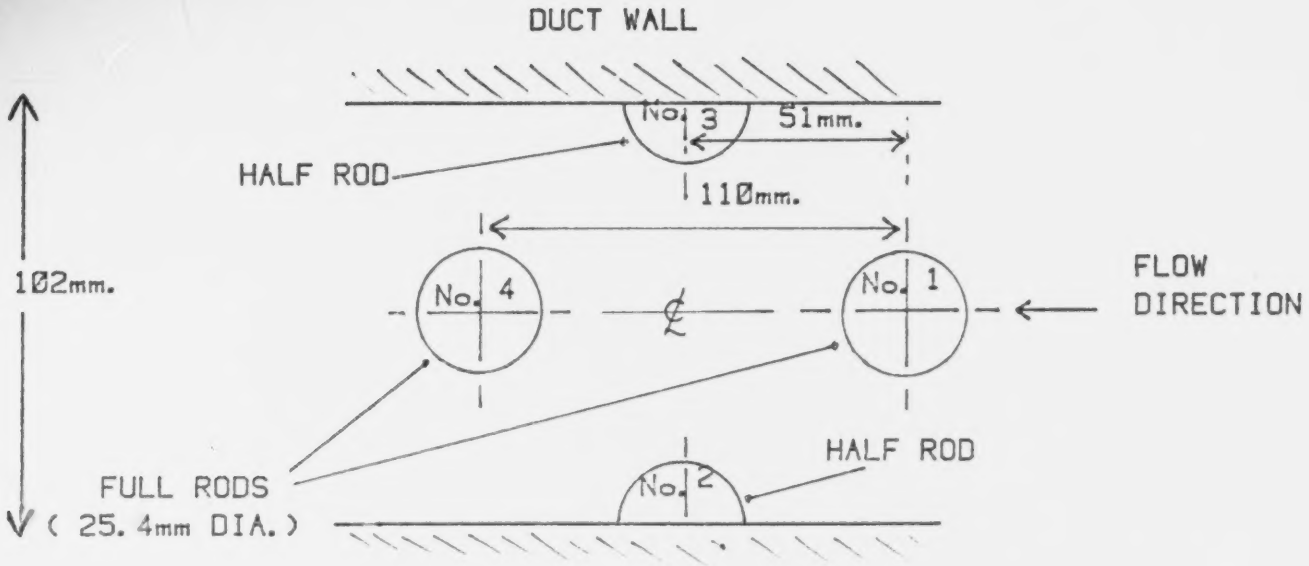


Figure 1a - PLAN OF ROD ARRANGEMENT.

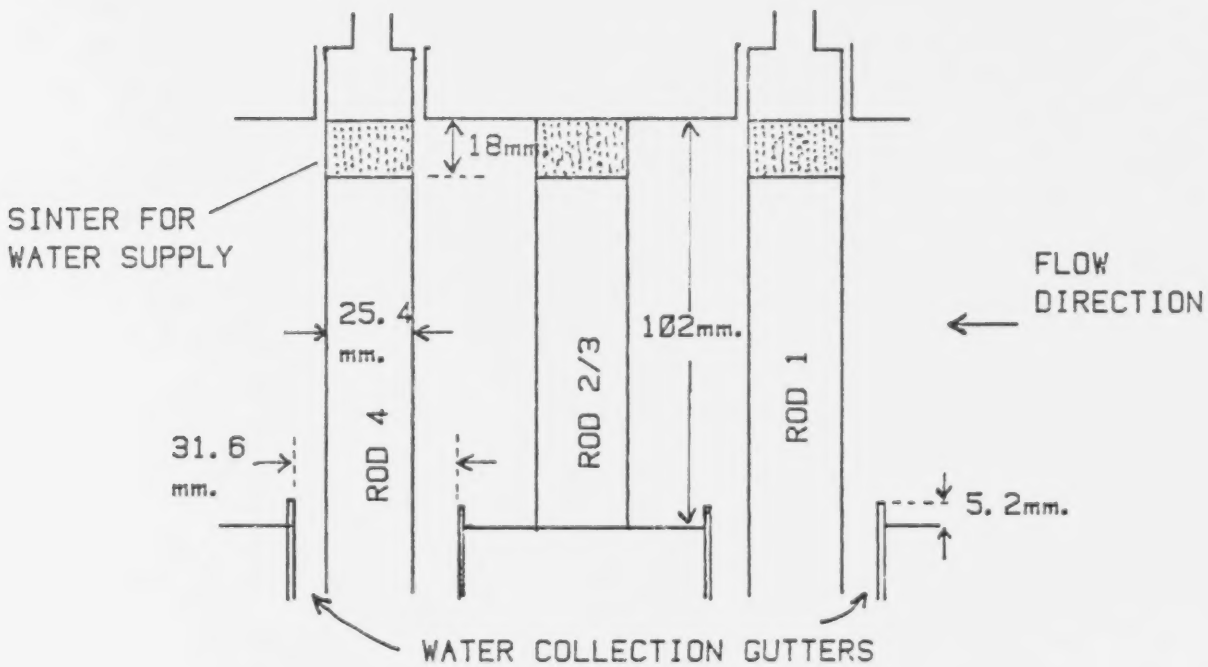


Figure 1b - ELEVATION OF ROD ARRANGEMENT

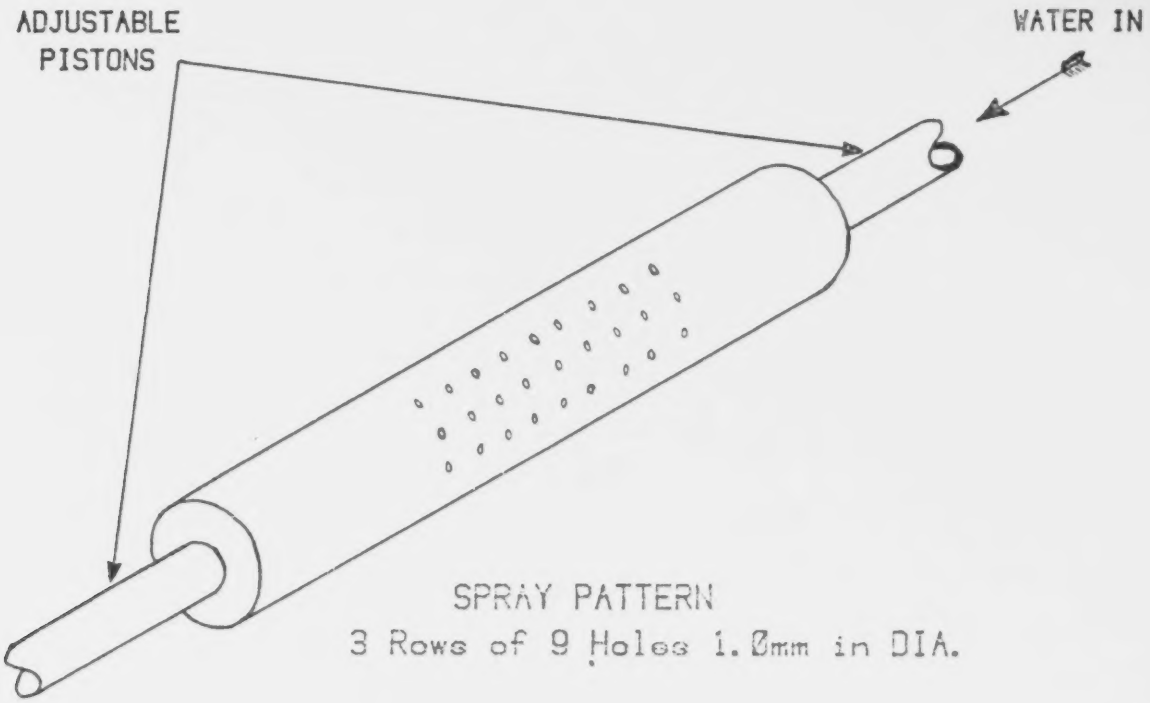


Fig. 2a. ENTRAINMENT SPRAY.

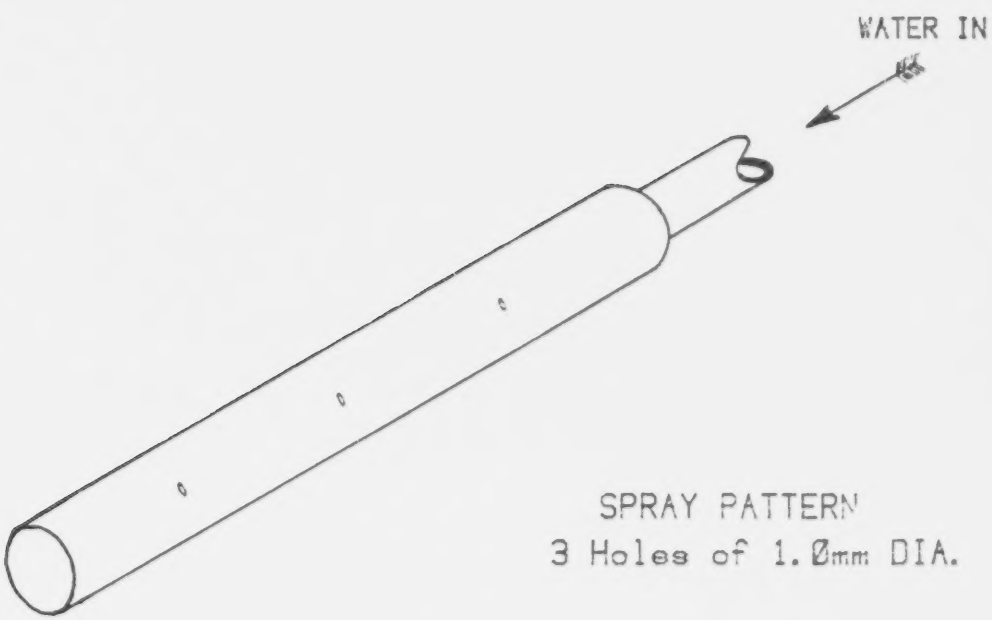
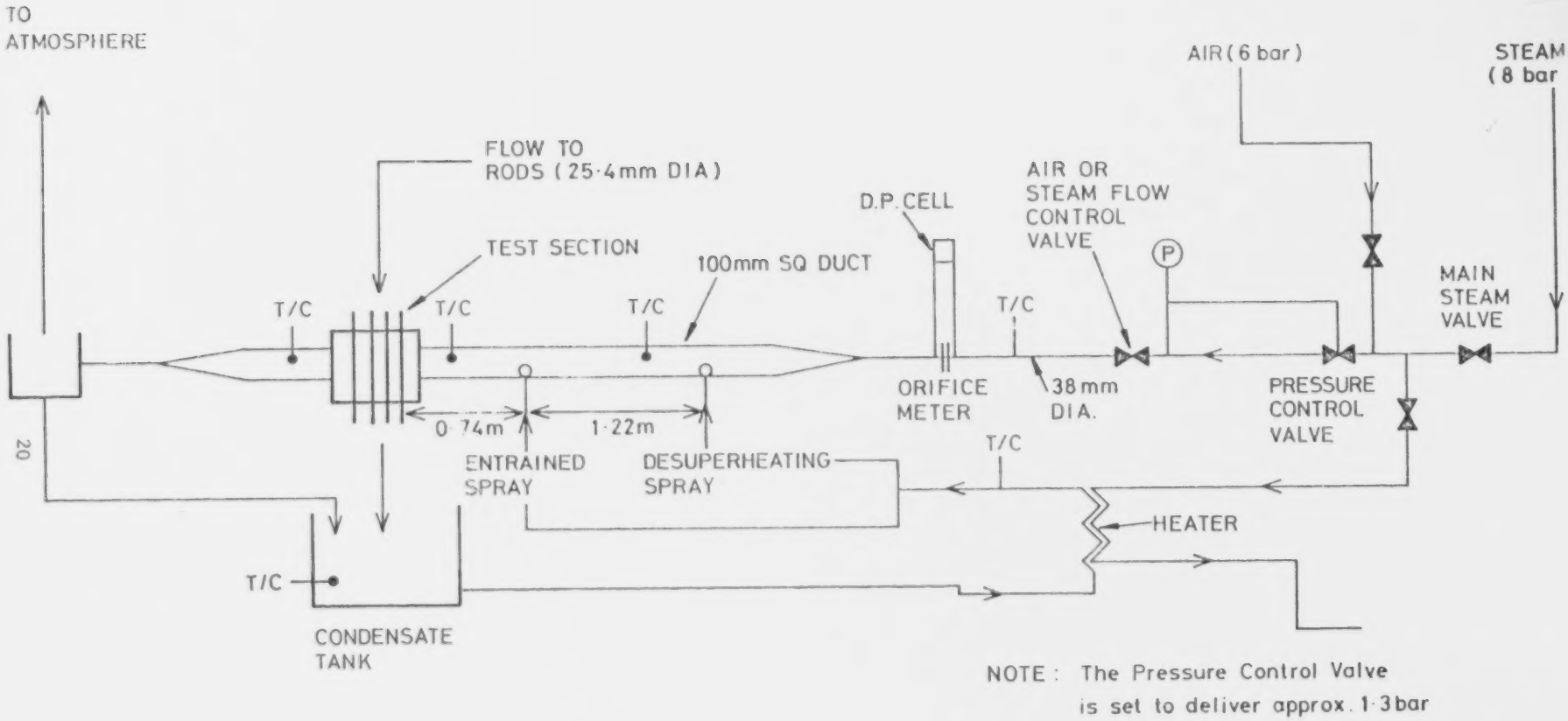


Fig. 2b. DE-SUPERHEATER SPRAY.



A.E.R.E. G.1873 FIG. 3.

HORIZONTAL STEAM RIG-FLOW DIAGRAM

Figure 4

ENTRAINMENT FROM A FALLING FILM WITH A CROSS-FLOW OF AIR, ROD 1.

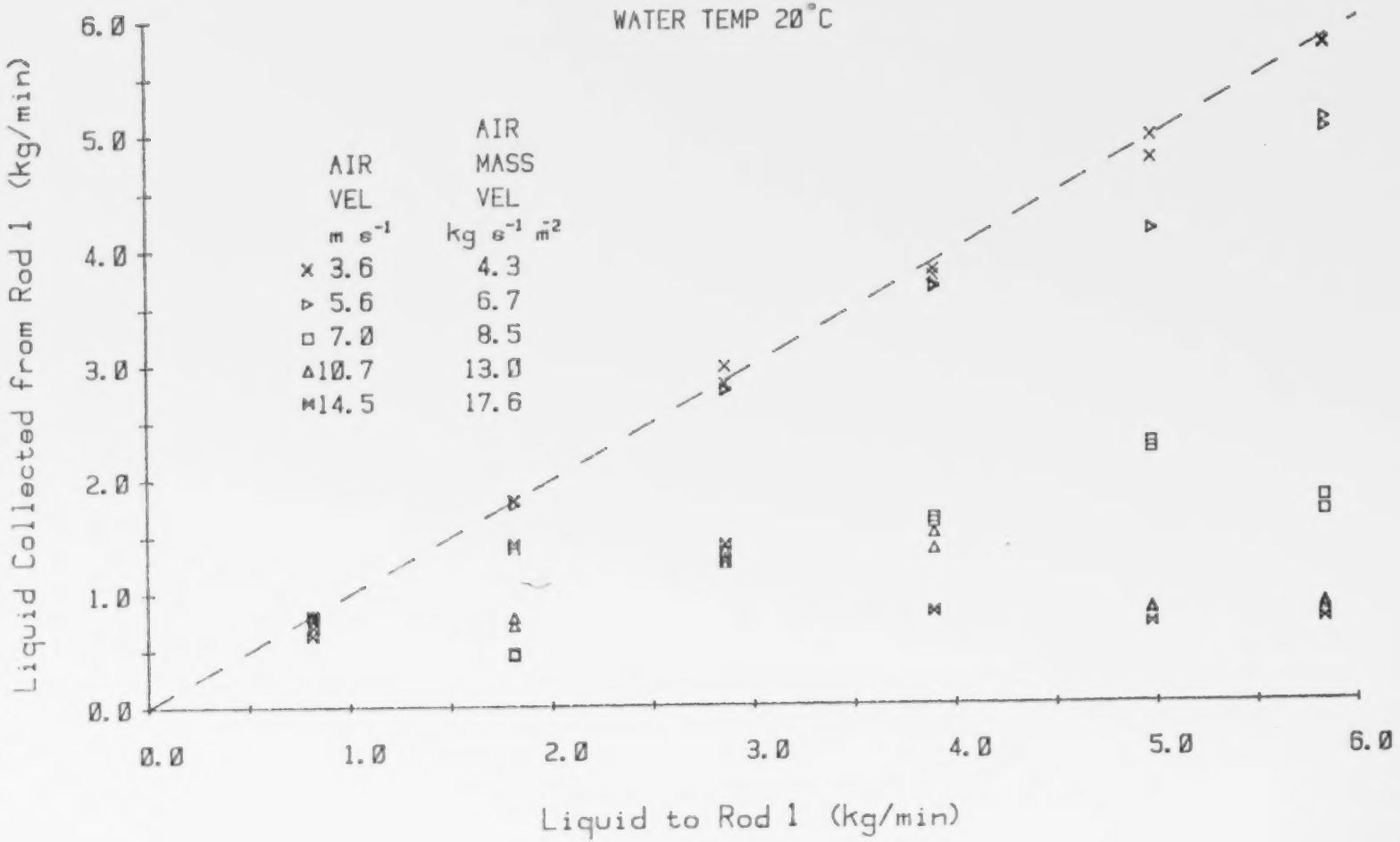


Figure 5

ENTRAINMENT FROM A FALLING FILM WITH A CROSS-FLOW OF AIR, ROD 4.

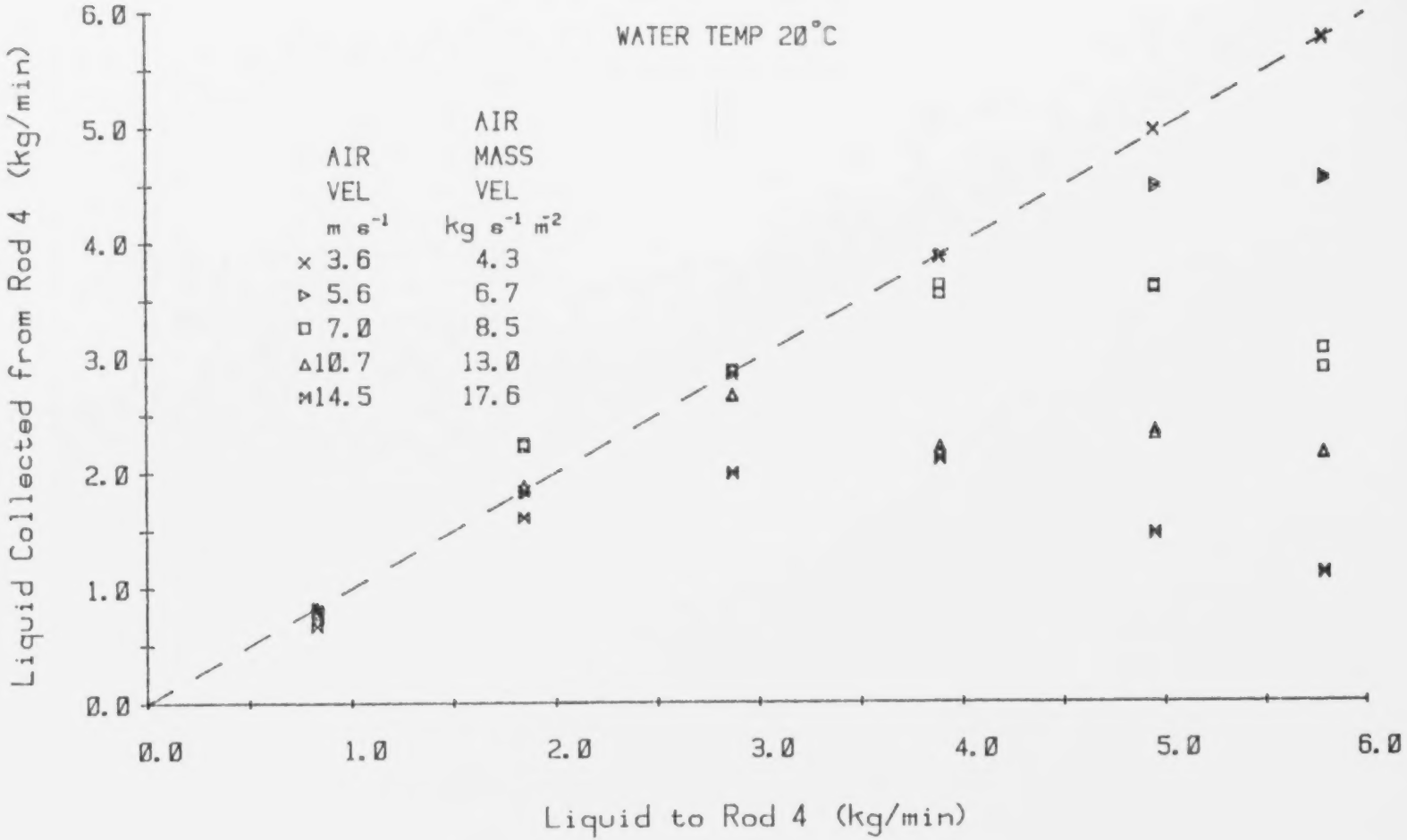


Figure 6

ENTRAINMENT STUDIES IN AIR.

HYSTERESIS EFFECT, RODS 1&4.

NO Liquid Supplied to Rod 4.

× = Increasing Flow. □ = Decreasing Flow.

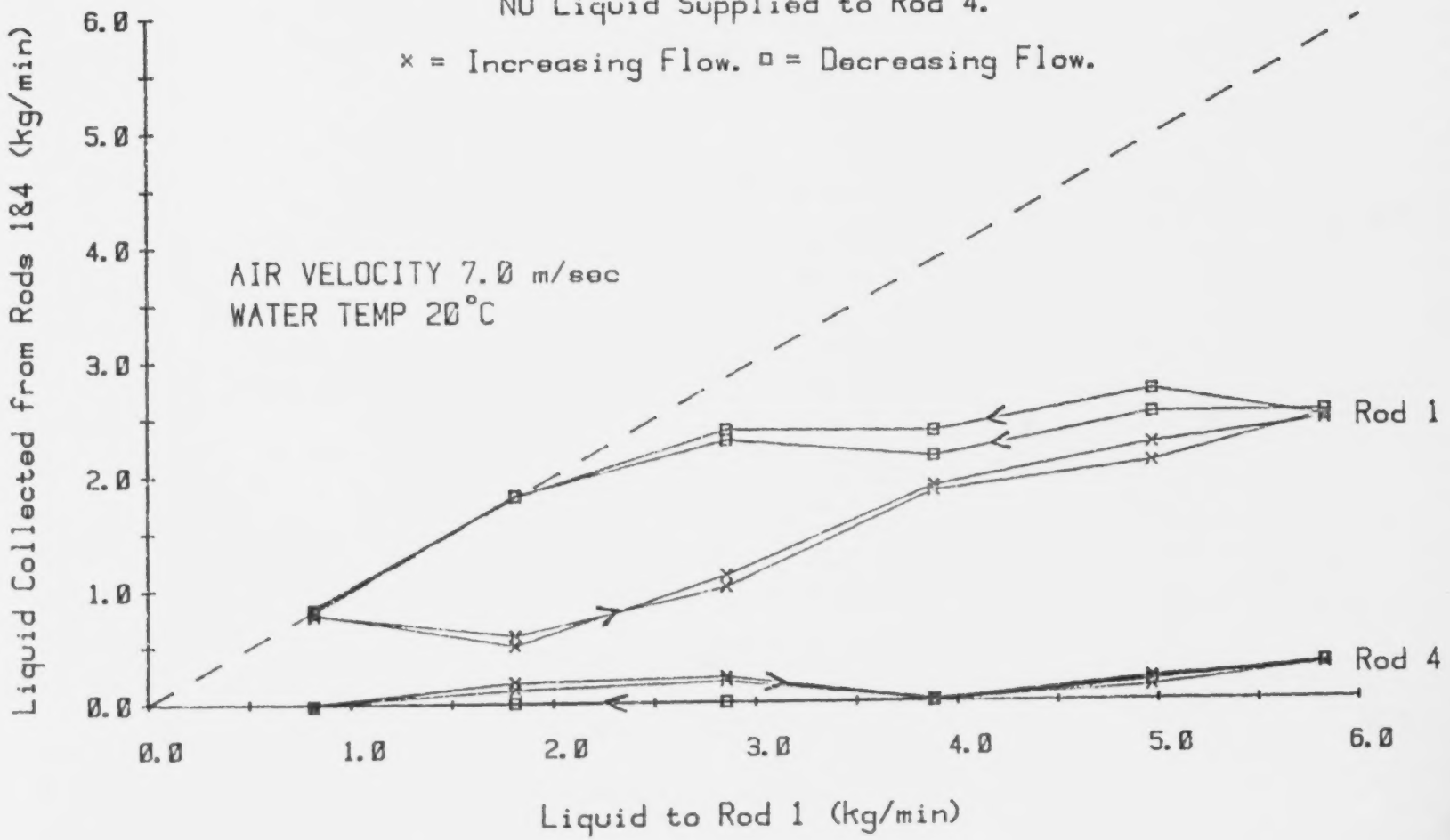


Figure 7

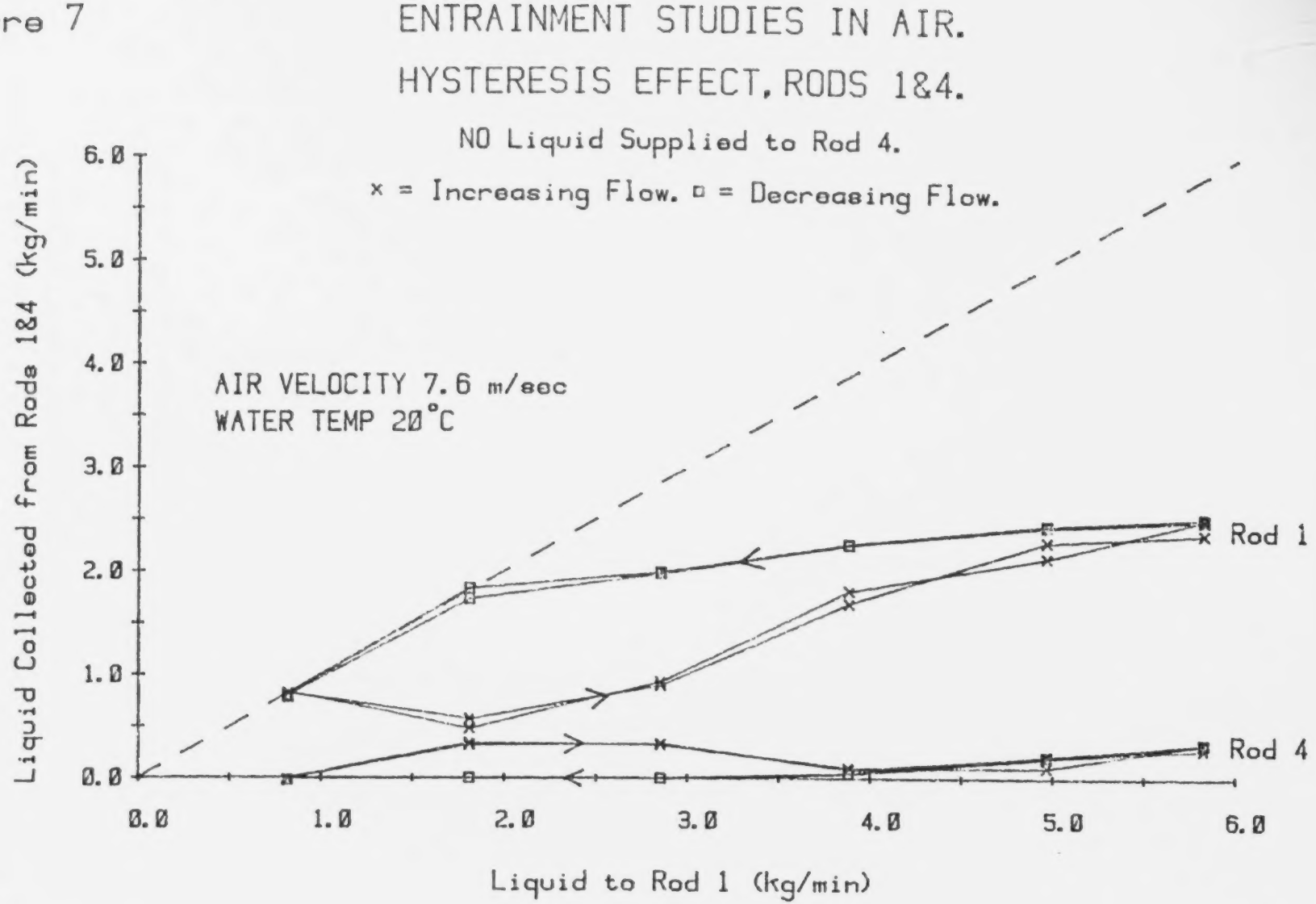

ENTRAINMENT STUDIES IN AIR.
HYSTERESIS EFFECT, RODS 1&4.
NO Liquid Supplied to Rod 4.
x = Increasing Flow. □ = Decreasing Flow.
AIR VELOCITY 7.6 m/sec
WATER TEMP 20°C
Liquid Collected from Rods 1&4 (kg/min)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Liquid to Rod 1 (kg/min)
Rod 1
Rod 4

Figure 8

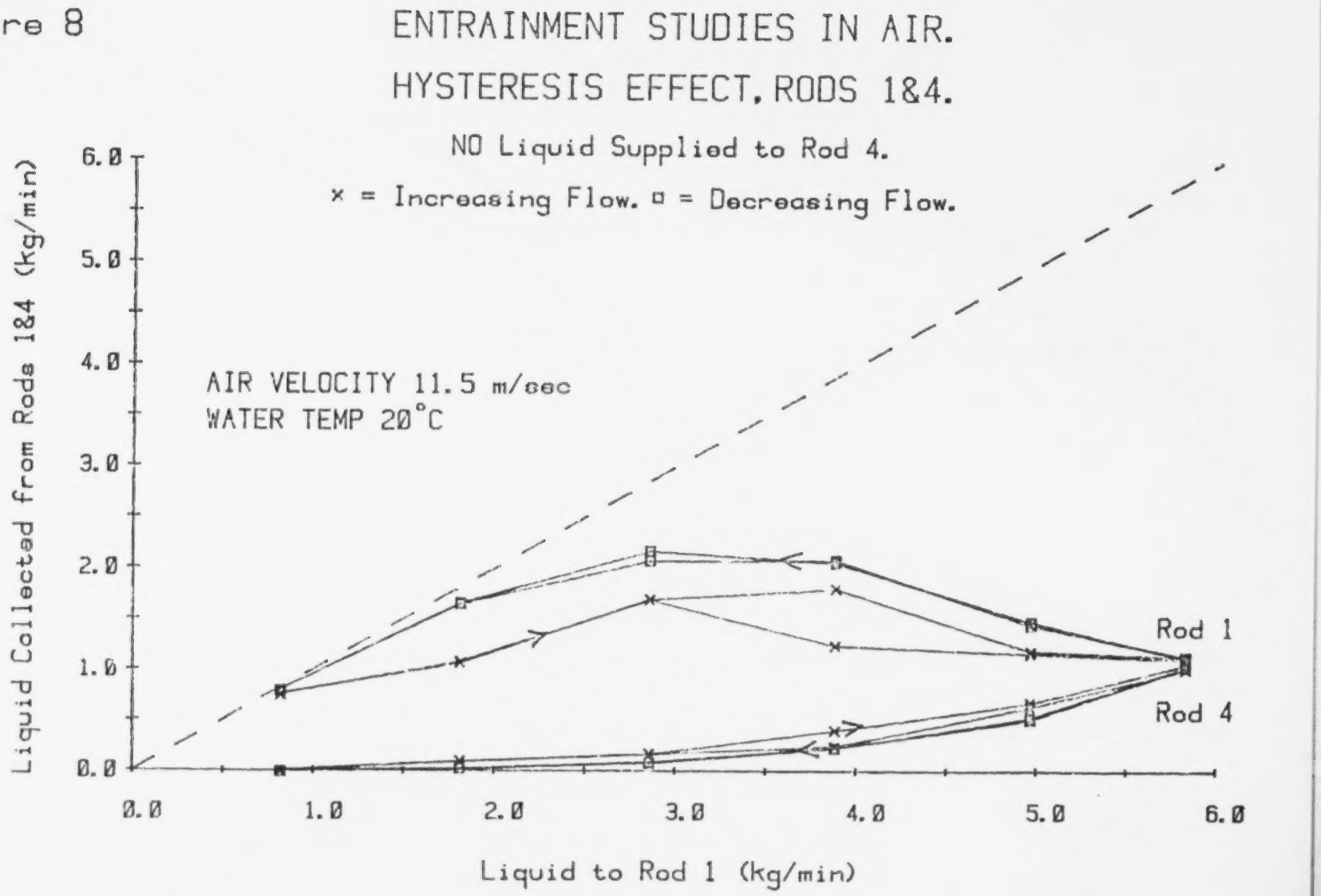

ENTRAINMENT STUDIES IN AIR.
HYSTERESIS EFFECT. RODS 1&4.
NO Liquid Supplied to Rod 4.
× = Increasing Flow. □ = Decreasing Flow.
AIR VELOCITY 11.5 m/sec
WATER TEMP 20°C
Liquid Collected from Rods 1&4 (kg/min)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Liquid to Rod 1 (kg/min)
Rod 1
Rod 4

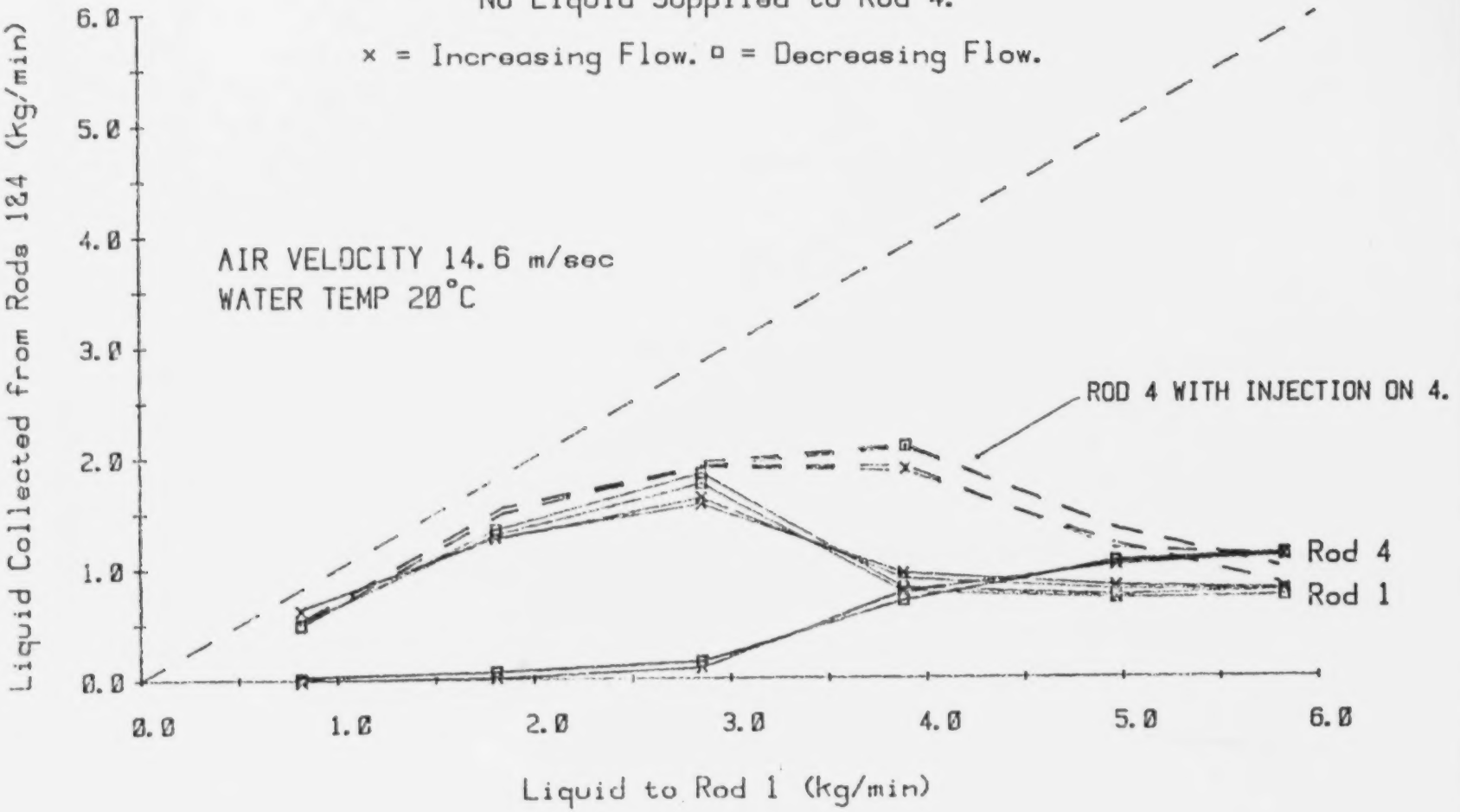
Figure 9

ENTRAINMENT STUDIES IN AIR.

HYSTERESIS EFFECT, RODS 1&4.

NO Liquid Supplied to Rod 4.

x = Increasing Flow. □ = Decreasing Flow.



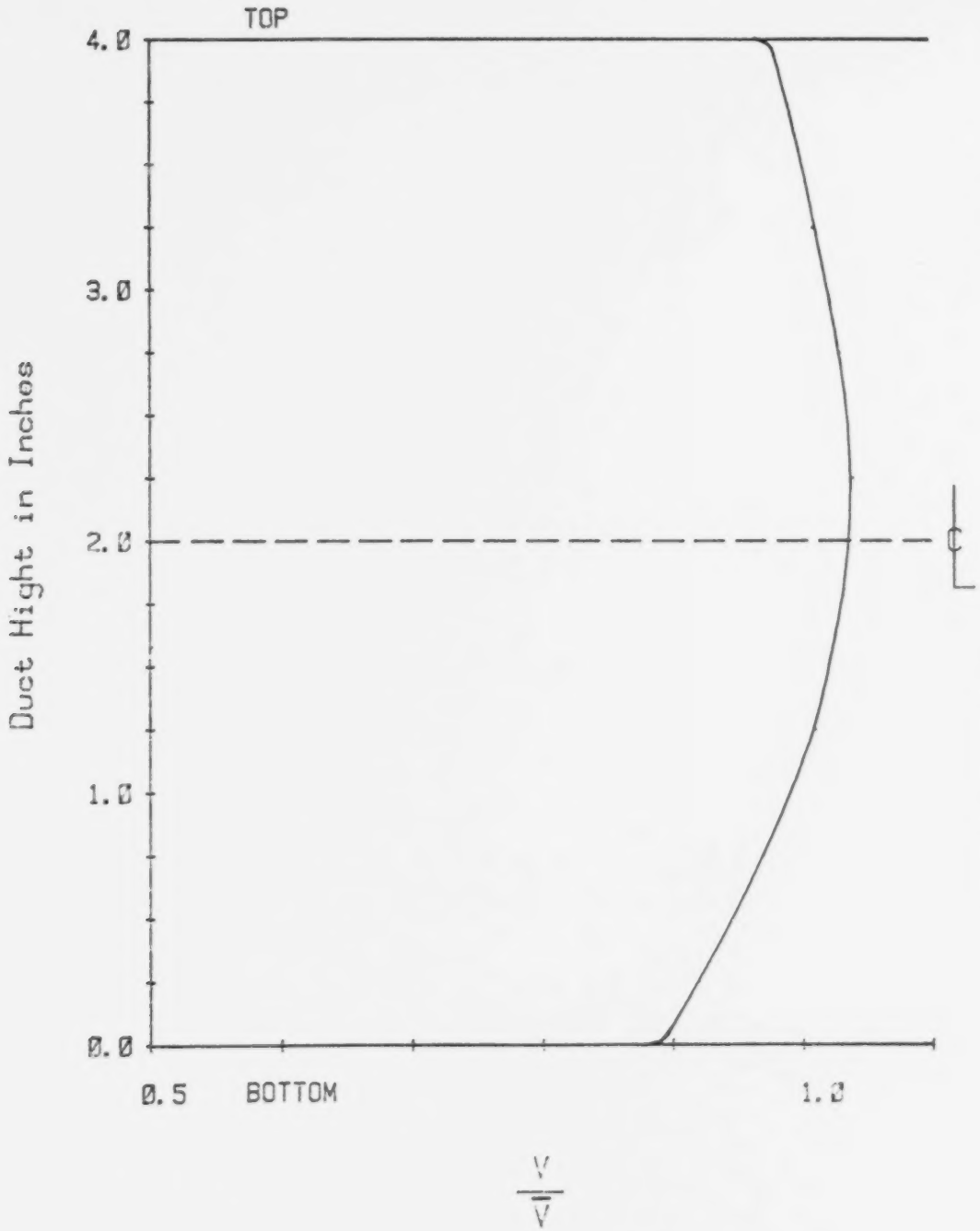


Figure 10

TYPICAL VELOCITY PROFILE

IN DUCT

Figure 11

ENTRAINMENT FROM A FALLING FILM WITH A CROSS-FLOW OF AIR, ROD 1.

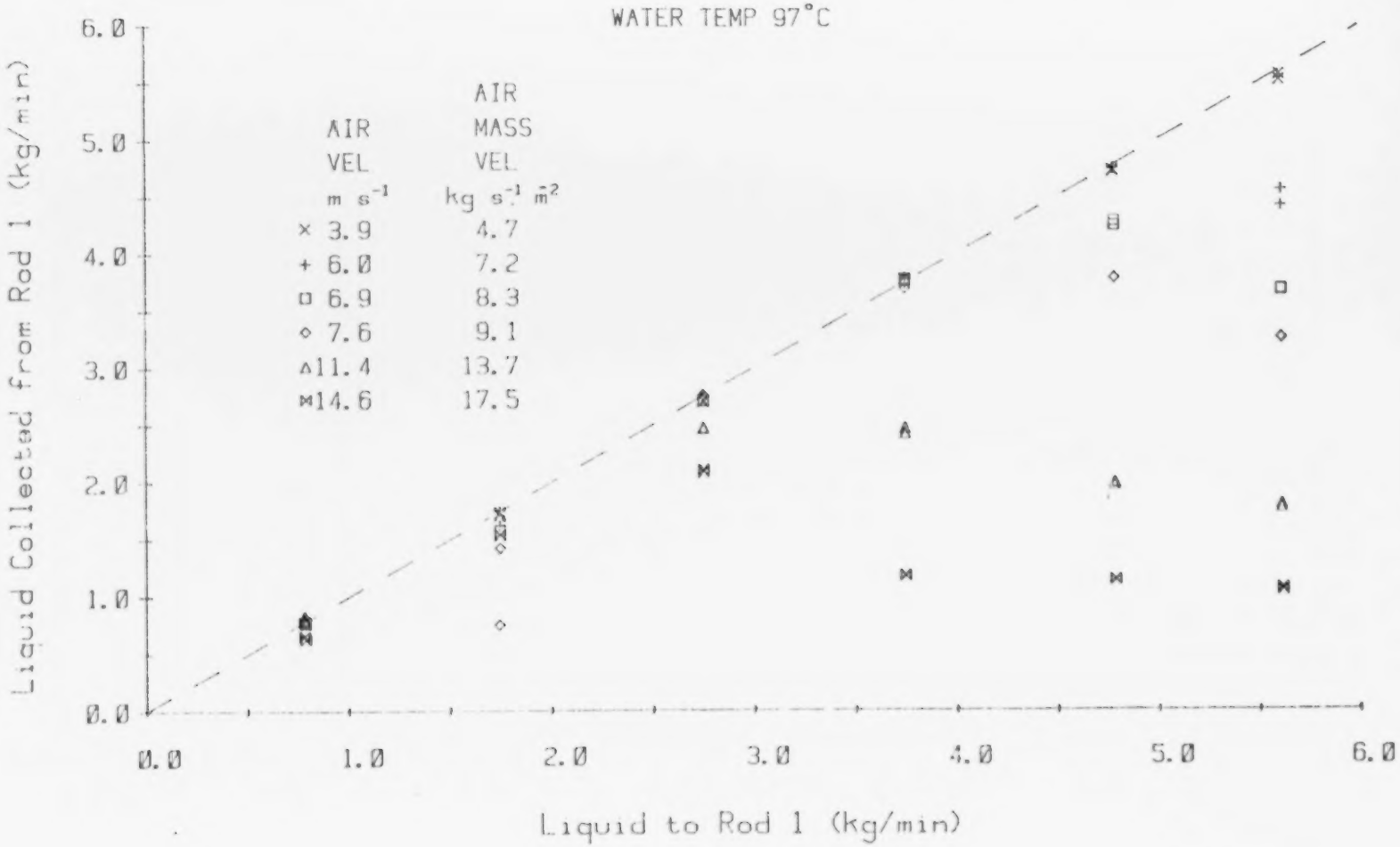


Figure 12

ENTRAINMENT FROM A FALLING FILM WITH A CROSS-FLOW OF AIR. ROD 4.

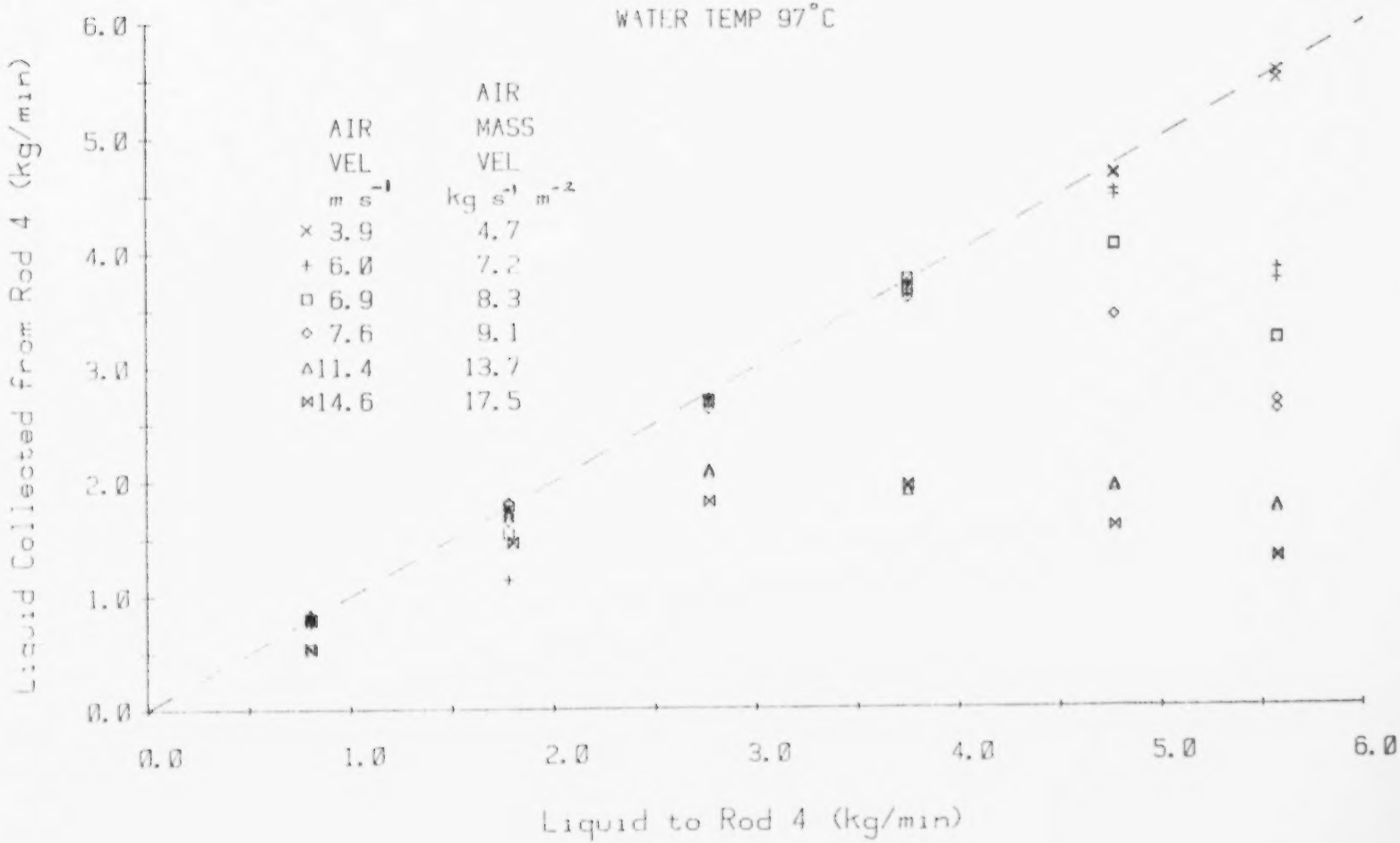


Figure 13

ENTRAINMENT STUDIES IN AIR.

HYSTERESIS EFFECT, RODS 1&4.

NO Liquid Supplied to Rod 4.

× = Increasing Flow. □ = Decreasing Flow.

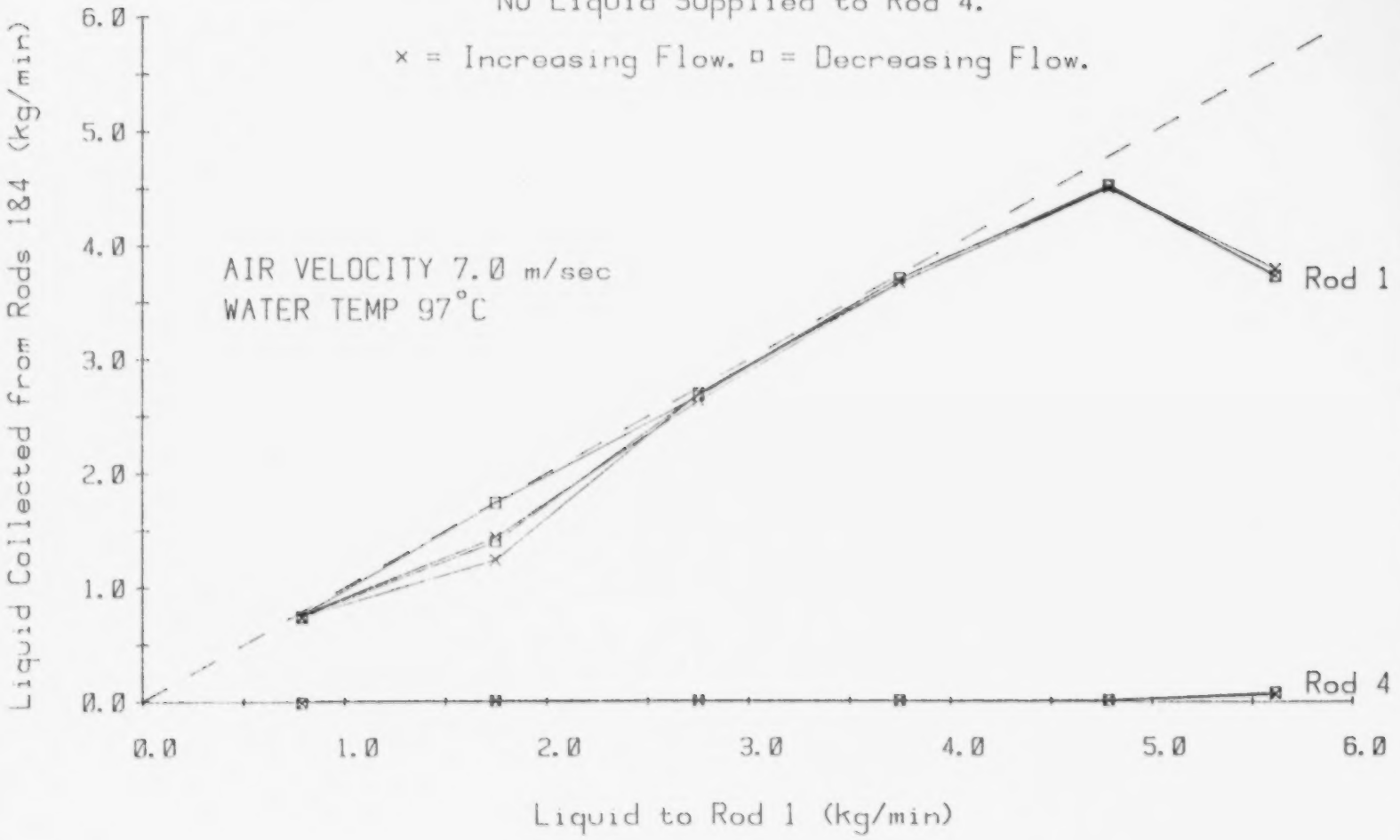


Figure 14

ENTRAINMENT STUDIES IN AIR.

HYSTERESIS EFFECT, RODS 1&4.

NO Liquid Supplied to Rod 4.

x = Increasing Flow. □ = Decreasing Flow.

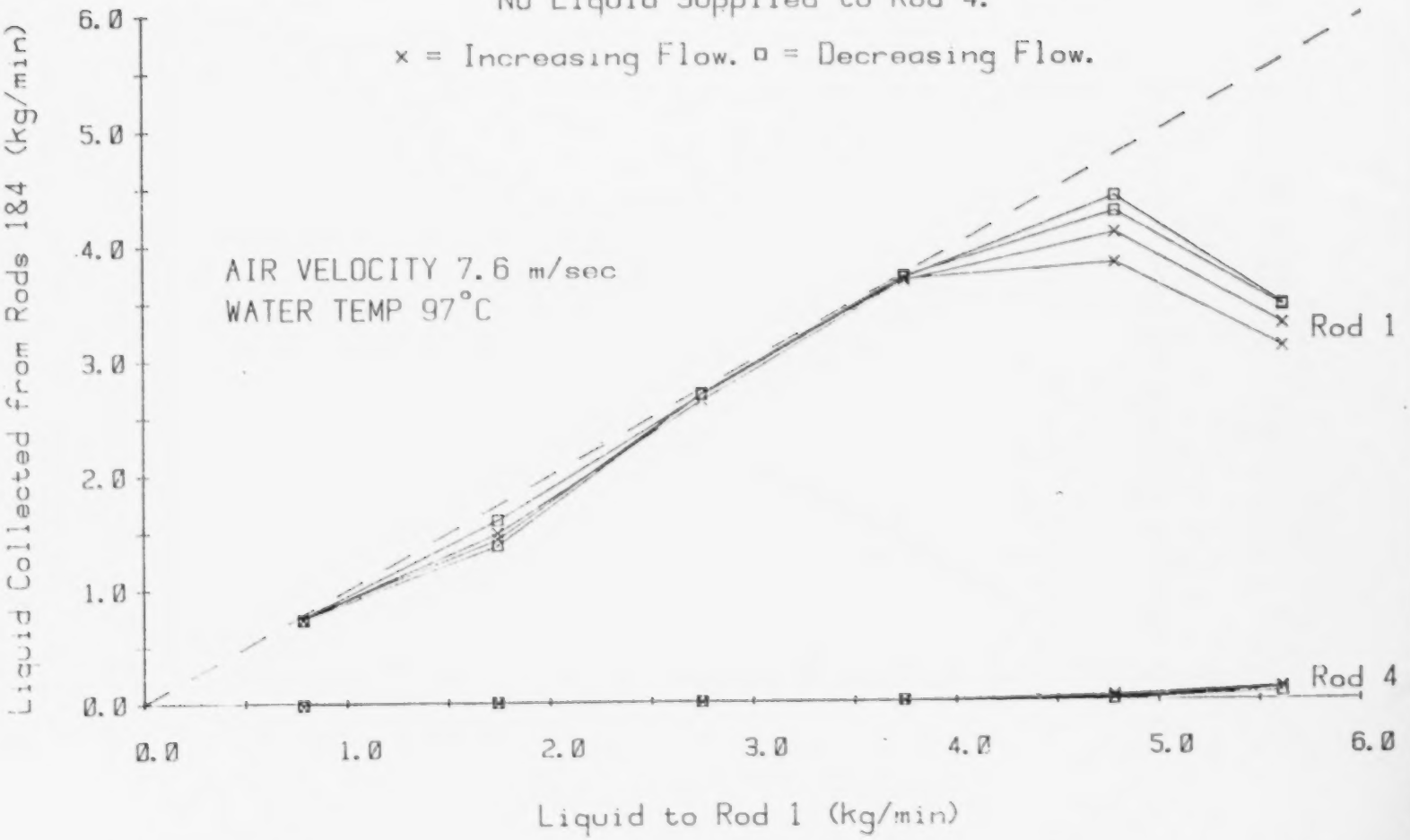


Figure 15

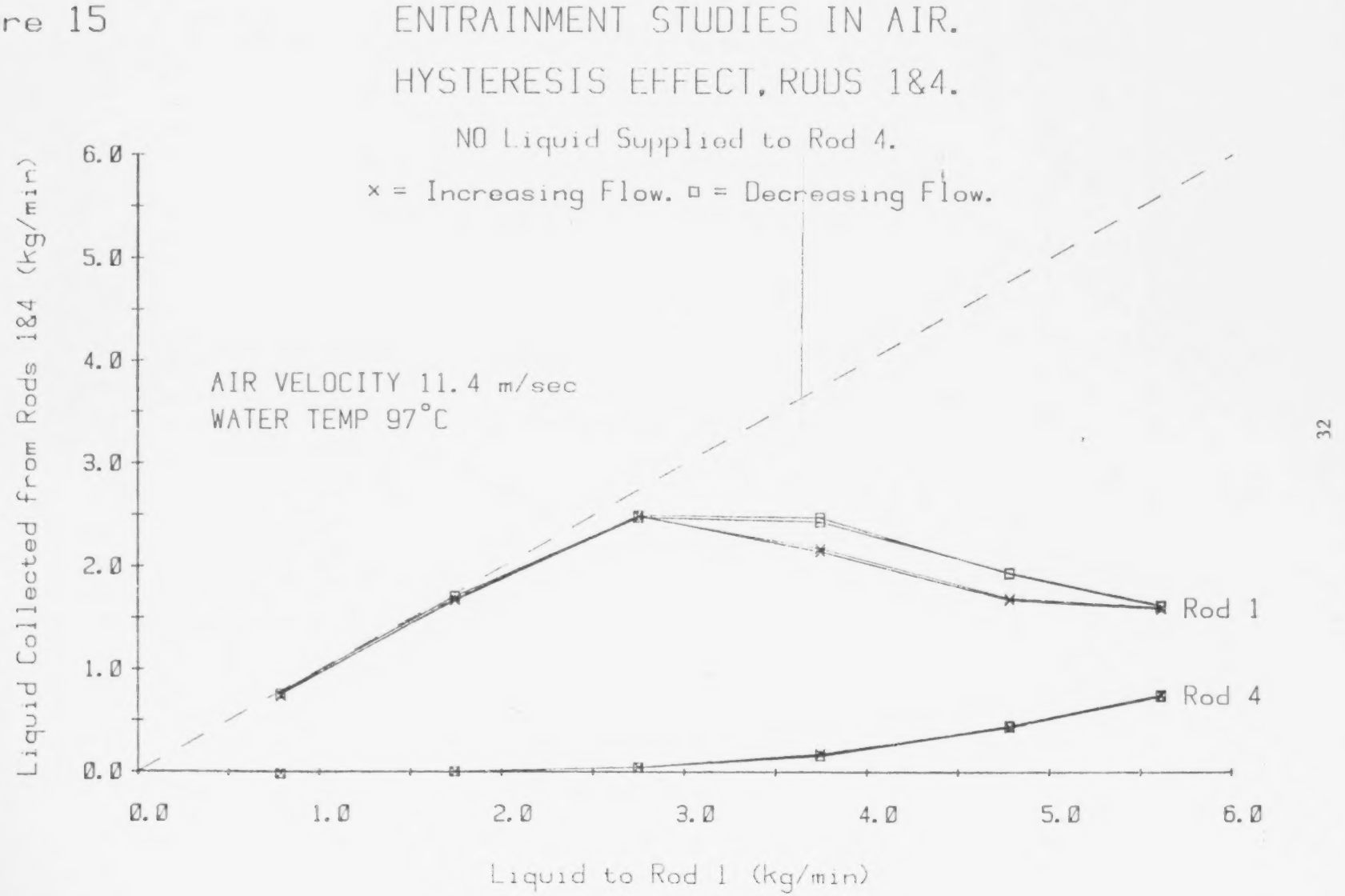

ENTRAINMENT STUDIES IN AIR.
HYSTERESIS EFFECT, RODS 1&4.
NO Liquid Supplied to Rod 4.
× = Increasing Flow. □ = Decreasing Flow.
AIR VELOCITY 11.4 m/sec
WATER TEMP 97°C
Liquid Collected from Rods 1&4 (kg/min)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Liquid to Rod 1 (kg/min)
Rod 1
Rod 4

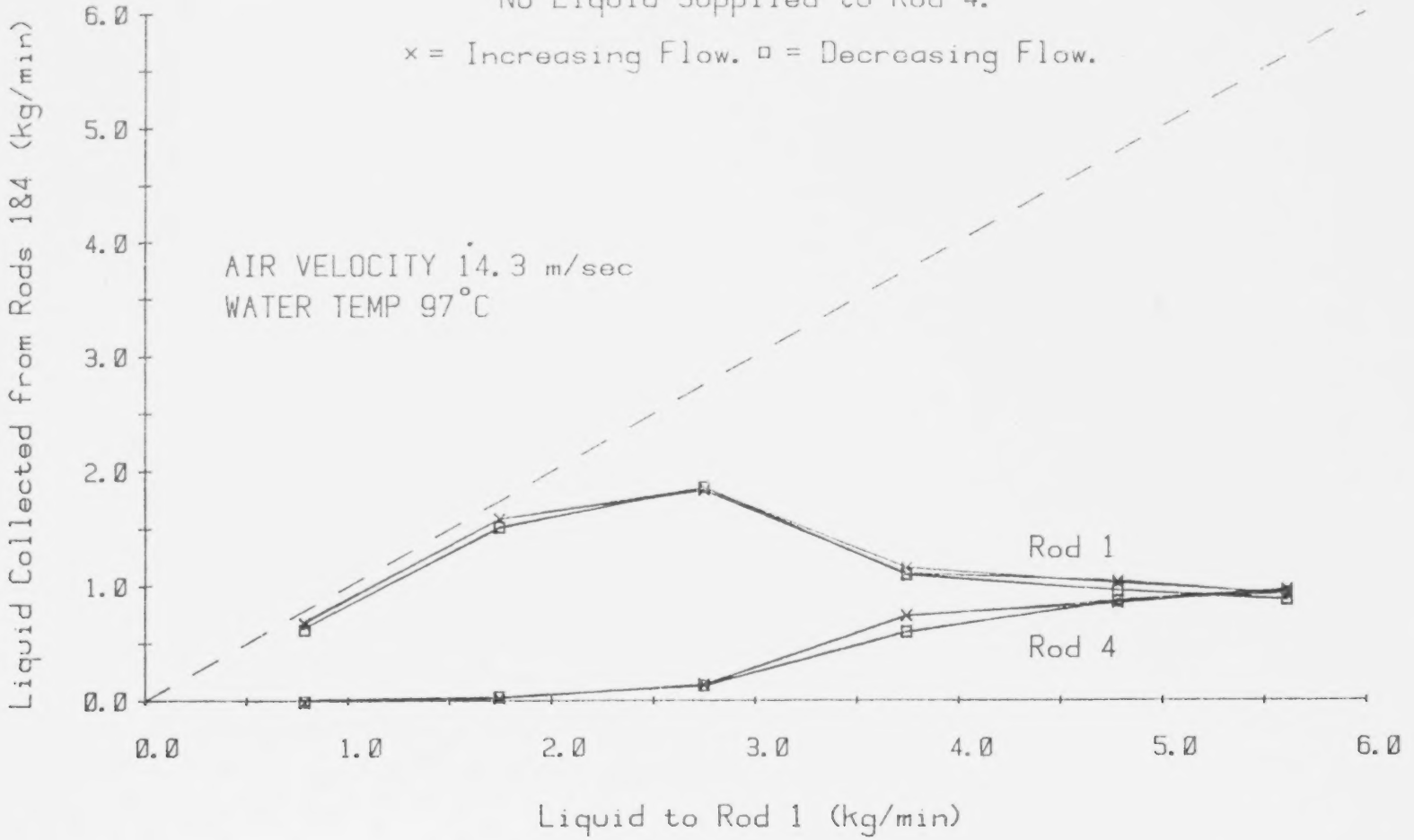
Figure 16

ENTRAINMENT STUDIES IN AIR.

HYSTERESIS EFFECT, RODS 1&4.

NO Liquid Supplied to Rod 4.

x = Increasing Flow. □ = Decreasing Flow.



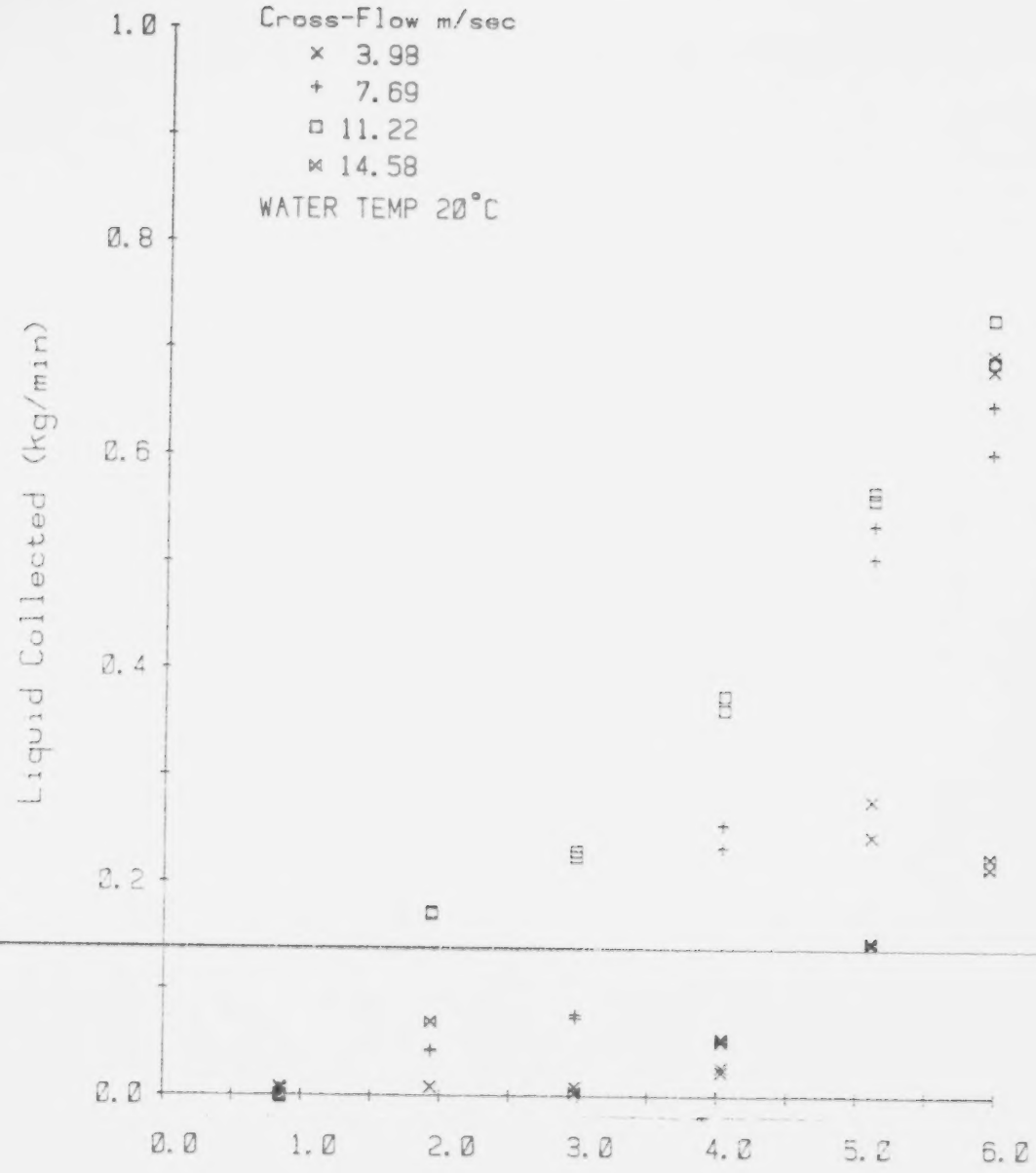


Figure 17

UPSTREAM INJECTION OF WATER IN AIR, ROD 1.

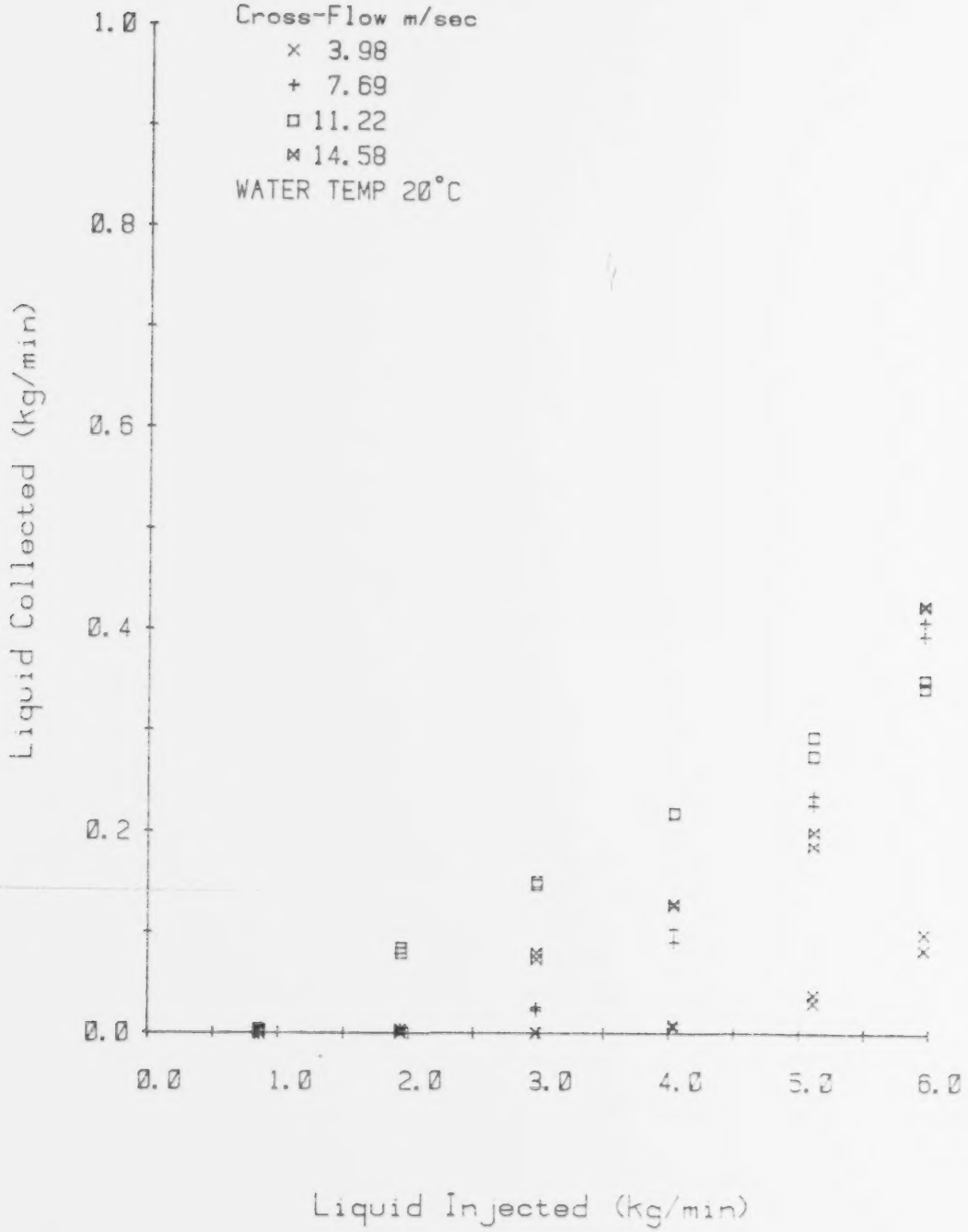


Figure 18

UPSTREAM INJECTION OF WATER:

IN AIR, ROD 4.

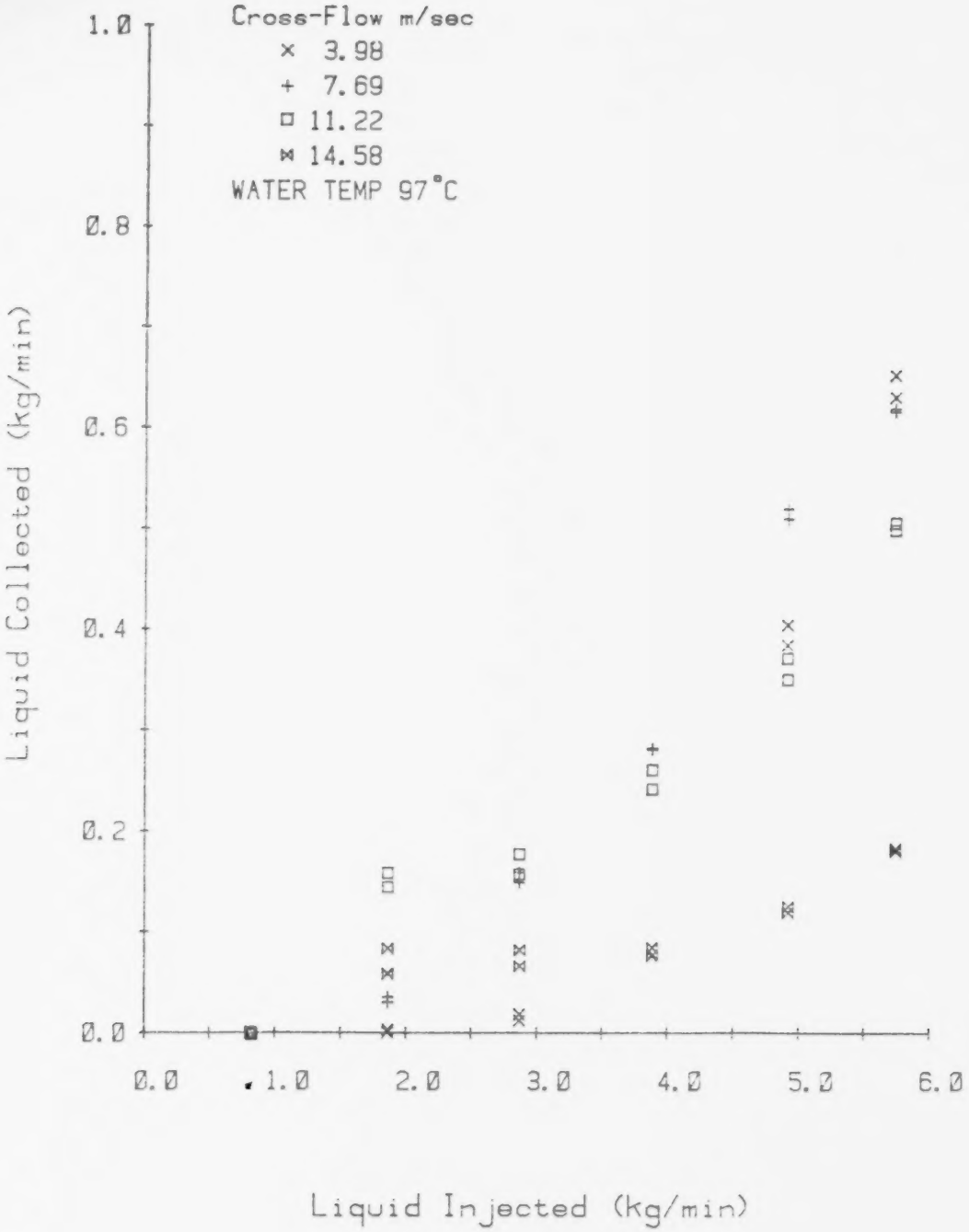


Figure 19

UPSTREAM INJECTION OF WATER:

IN AIR, ROD 1.

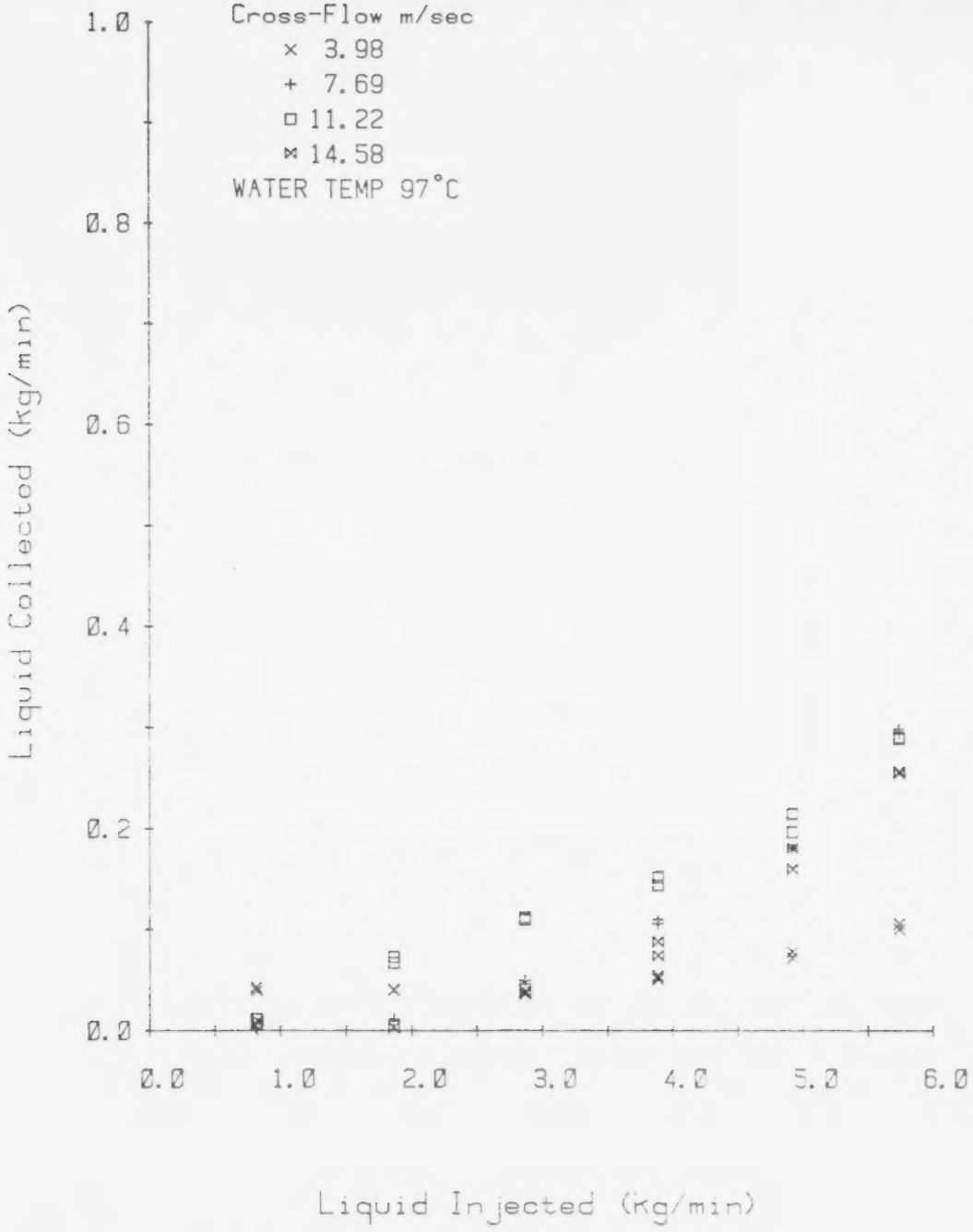


Figure 20

UPSTREAM INJECTION OF WATER:

IN AIR, ROD 1.

Figure 21

ENTRAINMENT FROM A FALLING FILM WITH A CROSS-FLOW OF STEAM. ROD 1.

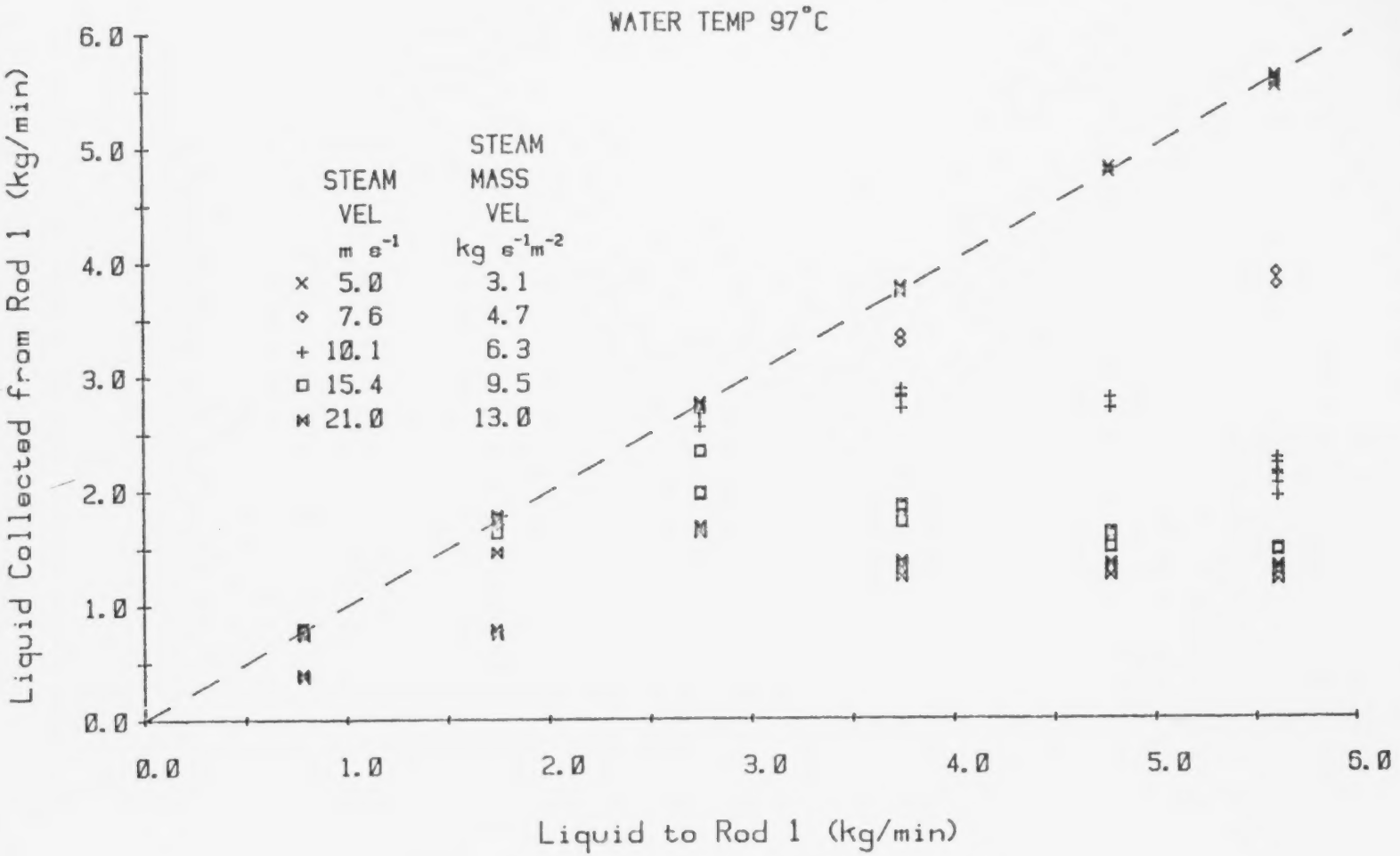


Figure 22

ENTRAINMENT FROM A FALLING FILM WITH A CROSS-FLOW OF STEAM, ROD 4.

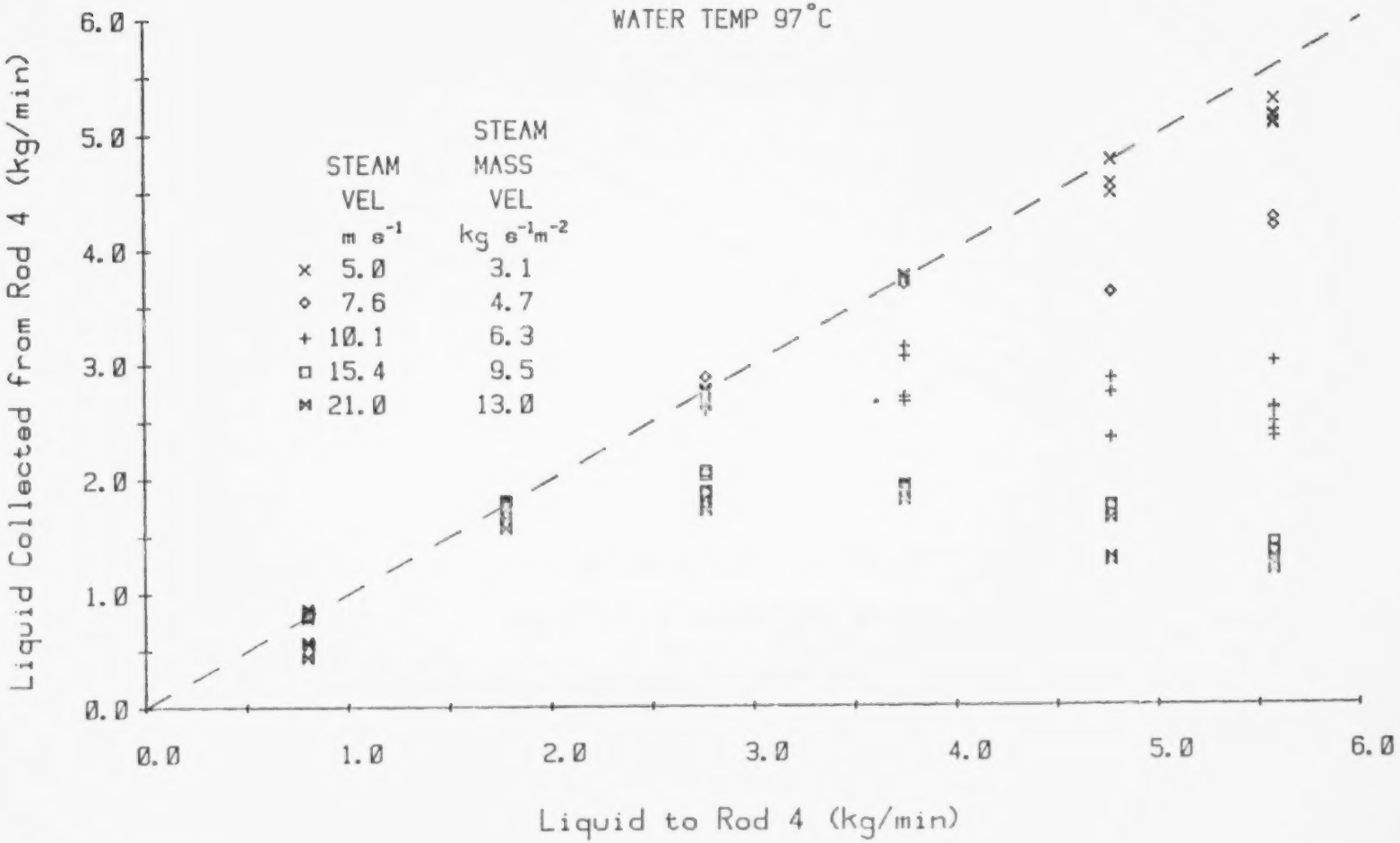


Figure 23

ENTRAINMENT STUDIES IN STEAM.
HYSTERESIS EFFECT, RODS 1&4.

NO Liquid Supplied to Rod 4.

x = Increasing Flow. □ = Decreasing Flow.

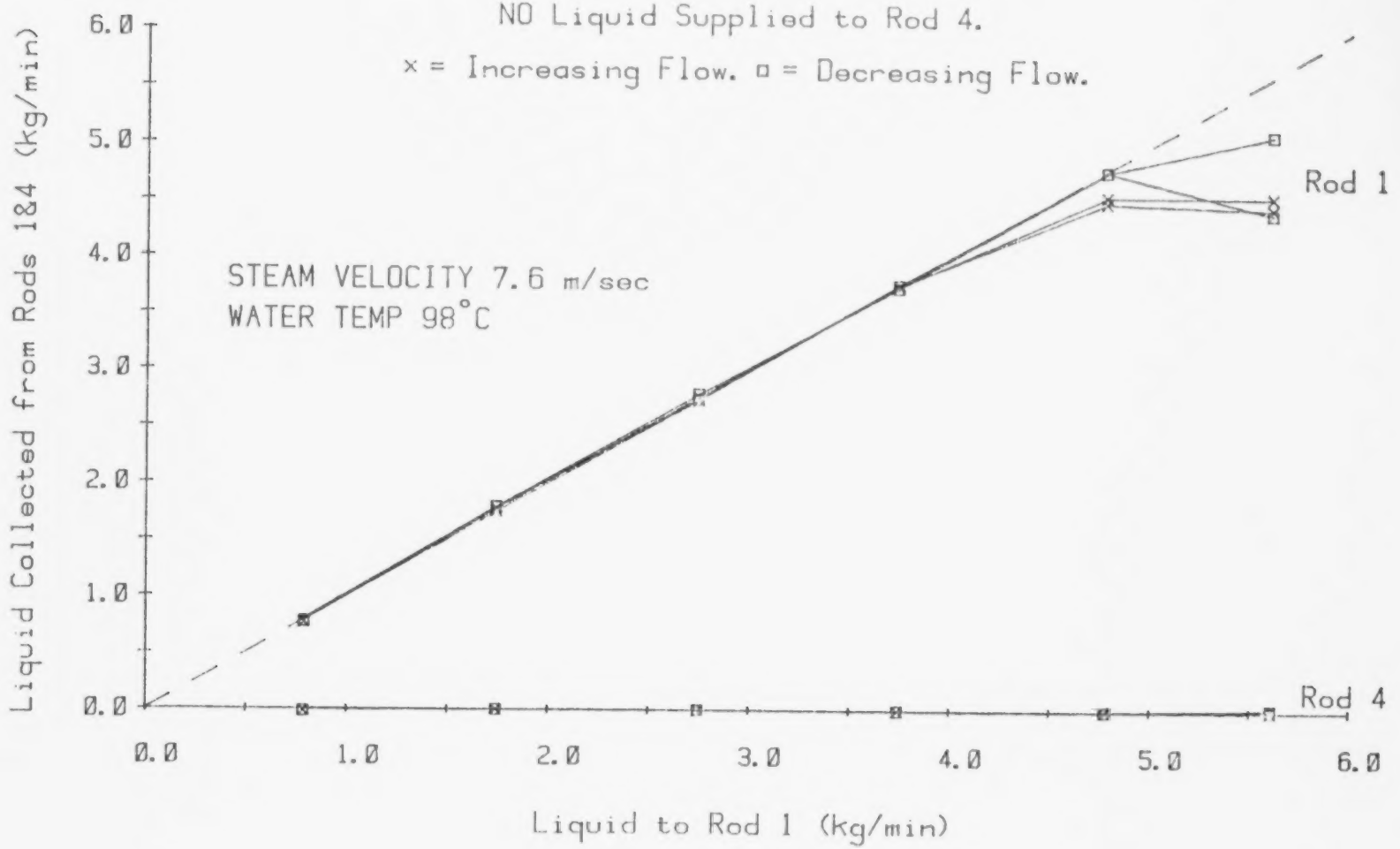


Figure 24

ENTRAINMENT STUDIES IN STEAM.

HYSTERESIS EFFECT, RODS 1&4.

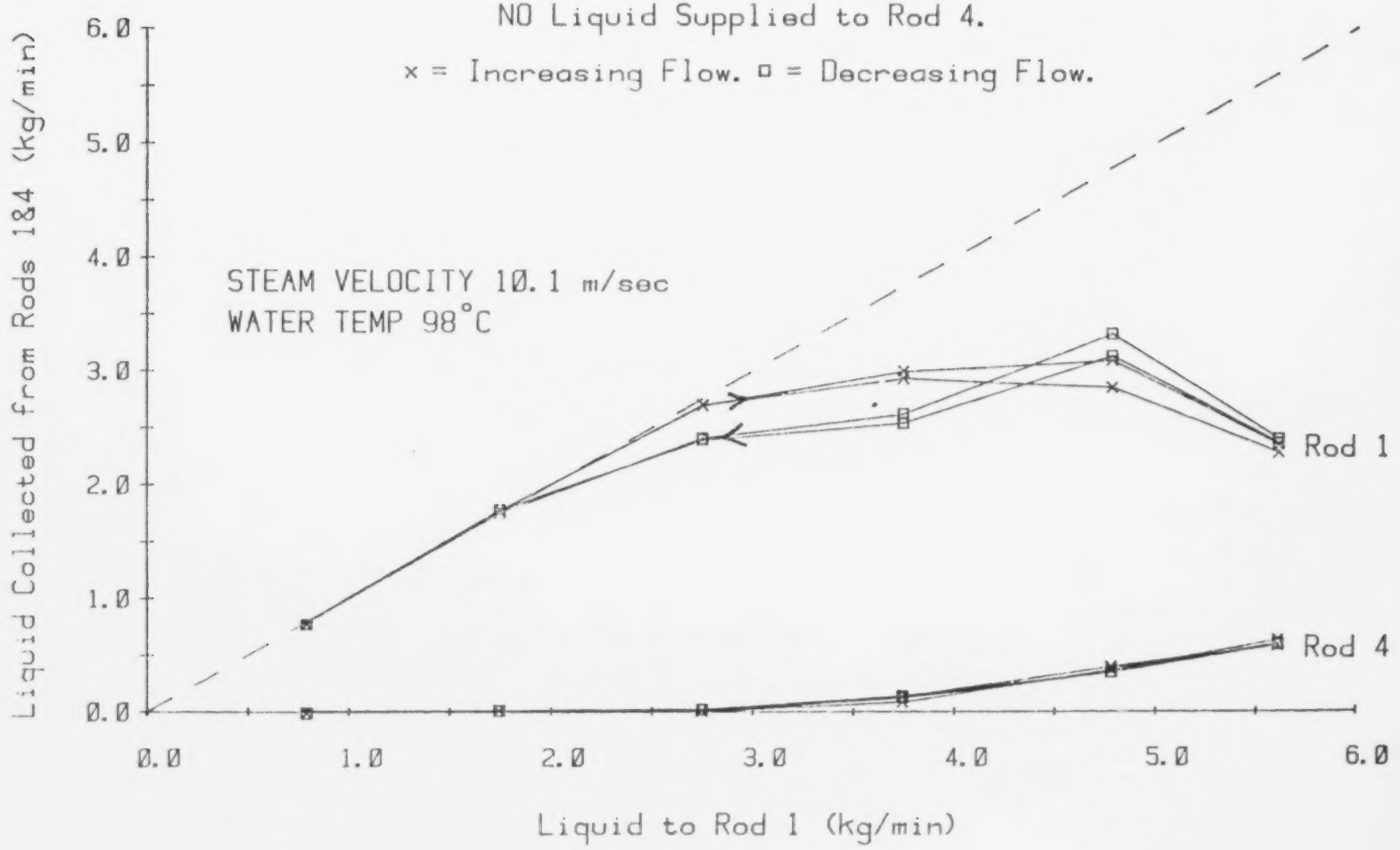


Figure 25

ENTRAINMENT STUDIES IN STEAM.
HYSTERESIS EFFECT, RODS 1&4.

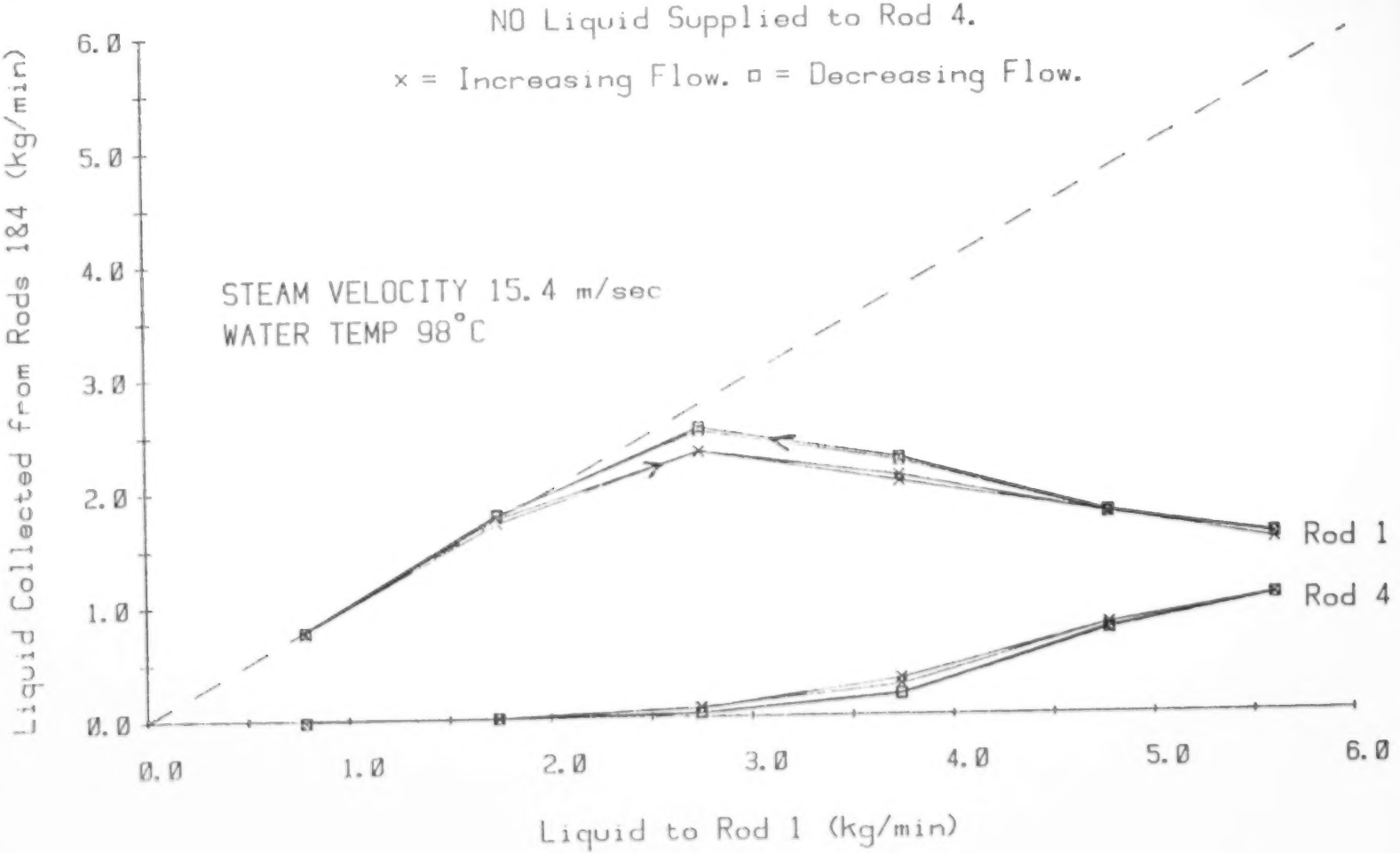


Figure 26

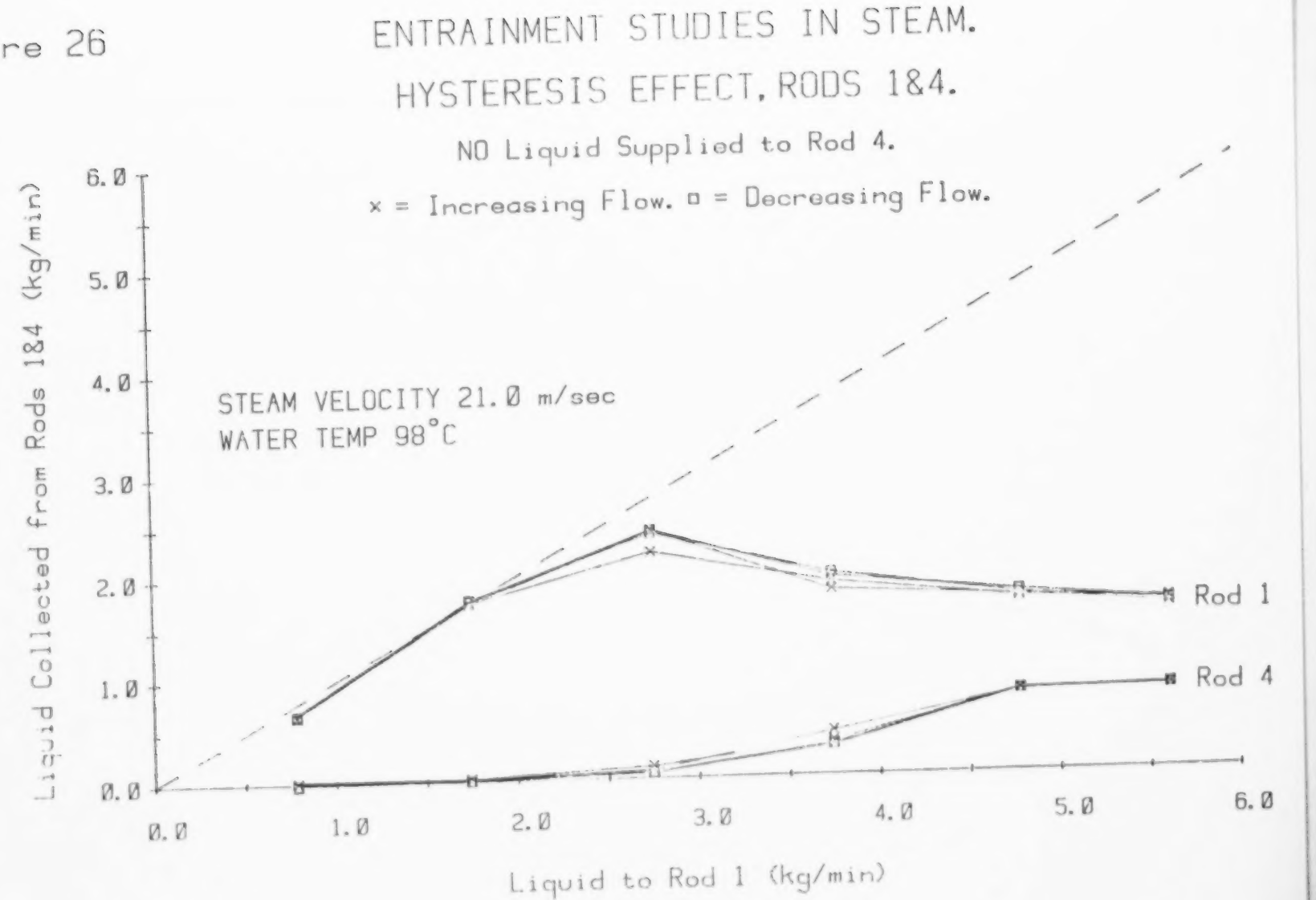

ENTRAINMENT STUDIES IN STEAM.
HYSTERESIS EFFECT, RODS 1&4.
NO Liquid Supplied to Rod 4.
x = Increasing Flow. □ = Decreasing Flow.
STEAM VELOCITY 21.0 m/sec
WATER TEMP 98°C
Liquid Collected from Rods 1&4 (kg/min)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Liquid to Rod 1 (kg/min)
Rod 1
Rod 4

Figure 27

ENTRAINMENT STUDIES IN STEAM.

EXTENDED ROD FLOW: 0.0---->9.0 kg/min

NO Liquid Supplied to Rod 4.

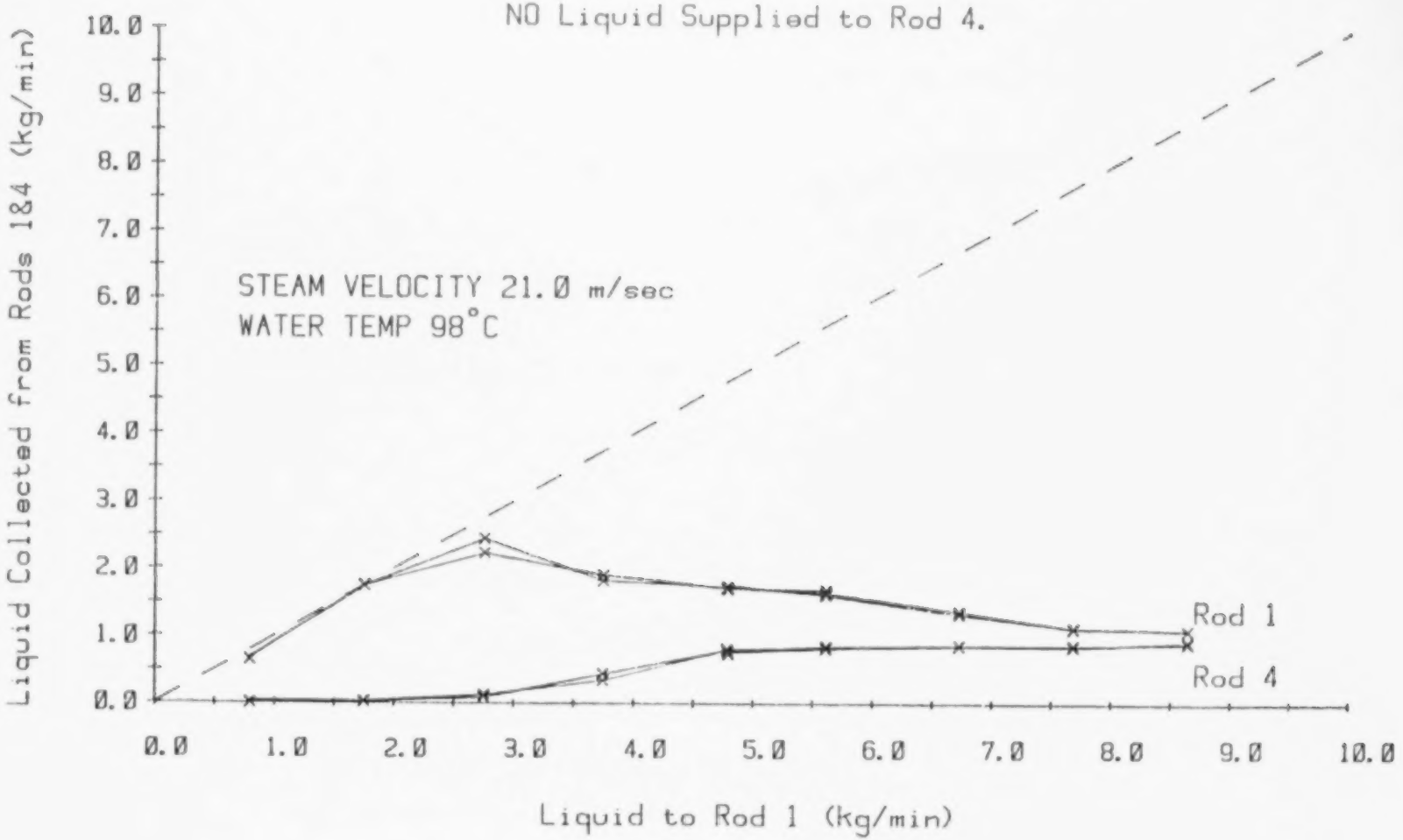
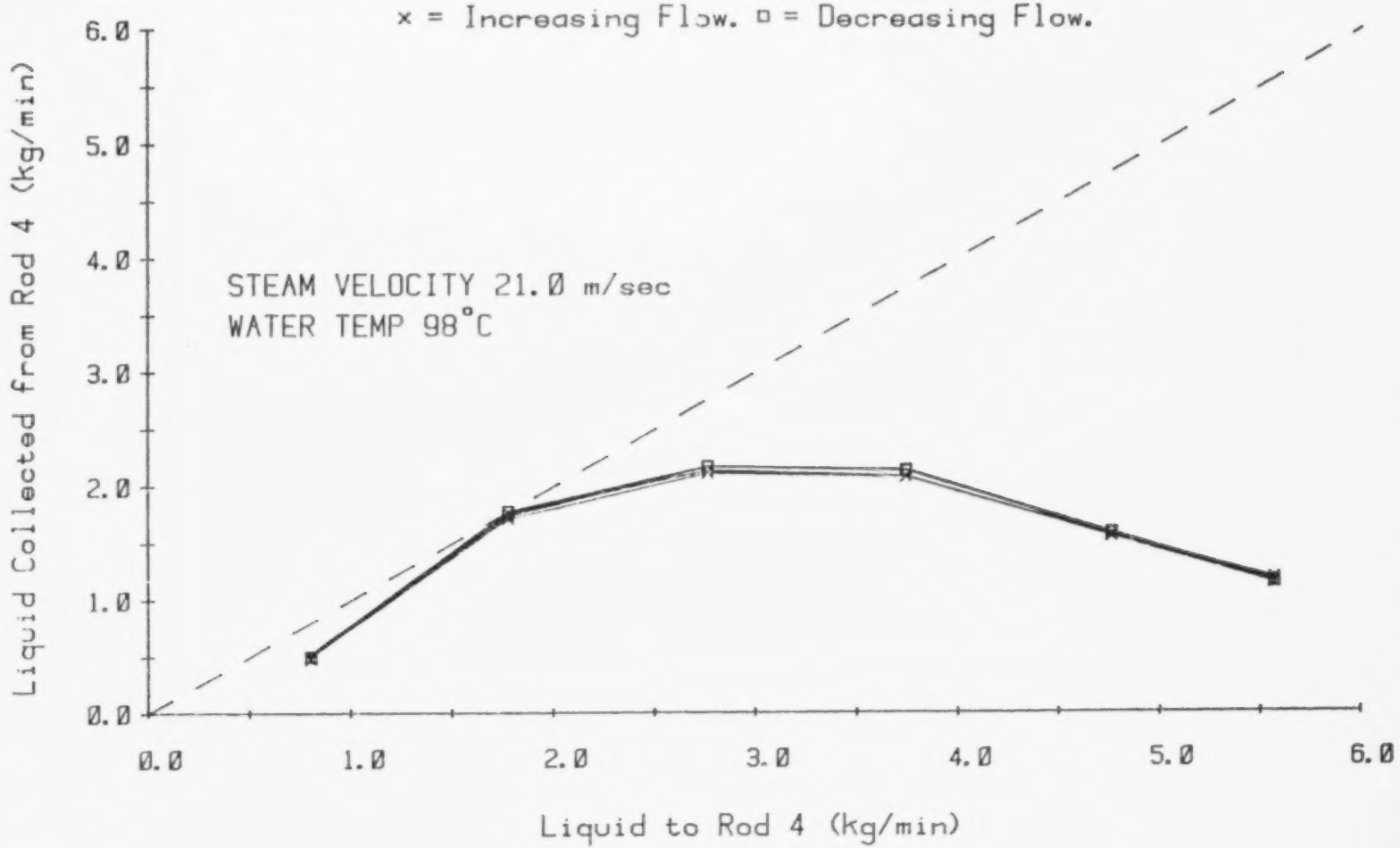


Figure 28

ENTRAINMENT FROM A FALLING FILM WITH A CROSS-FLOW OF STEAM, ROD 4.



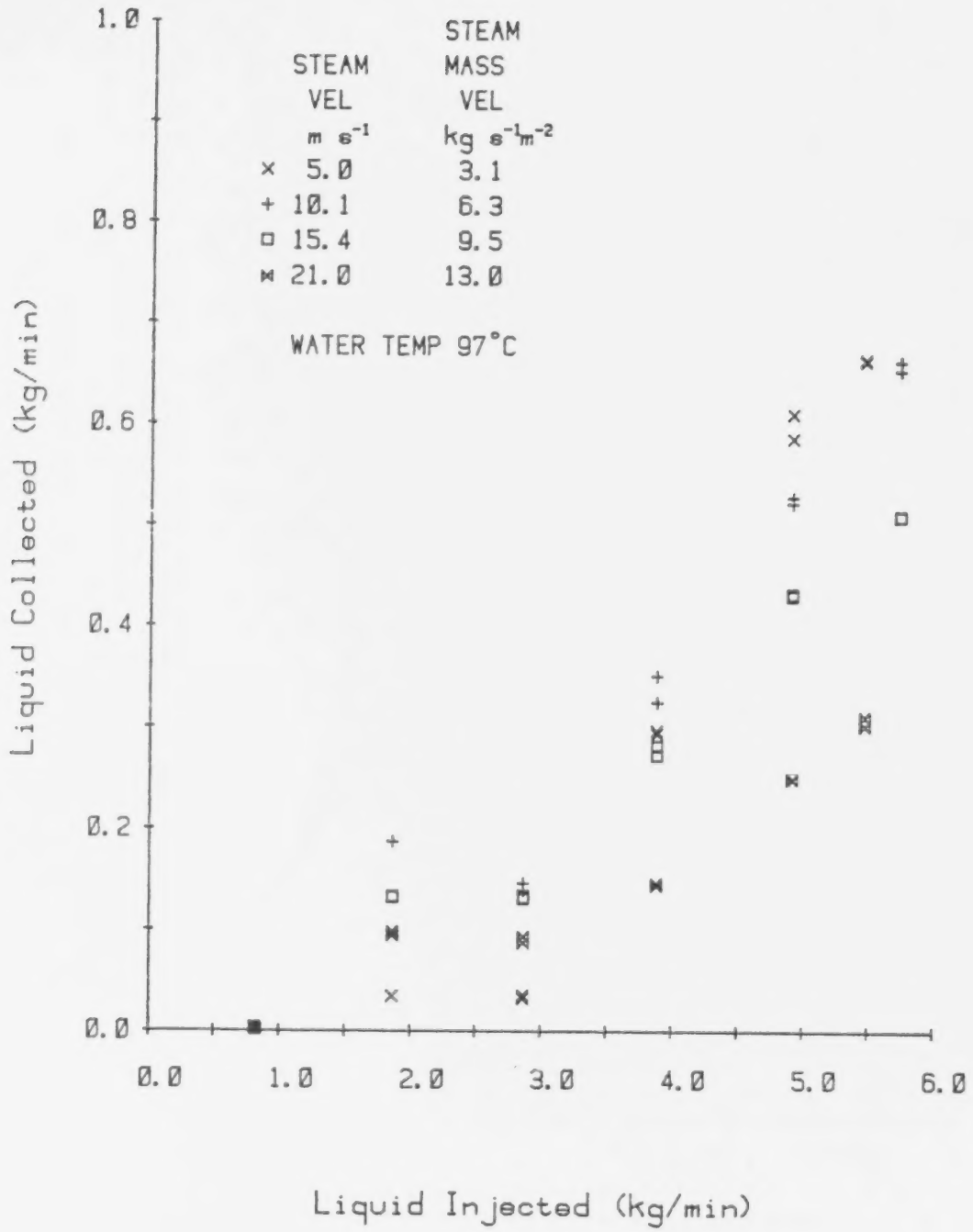


Figure 29

UPSTREAM INJECTION OF WATER:

IN STEAM, ROD 1.

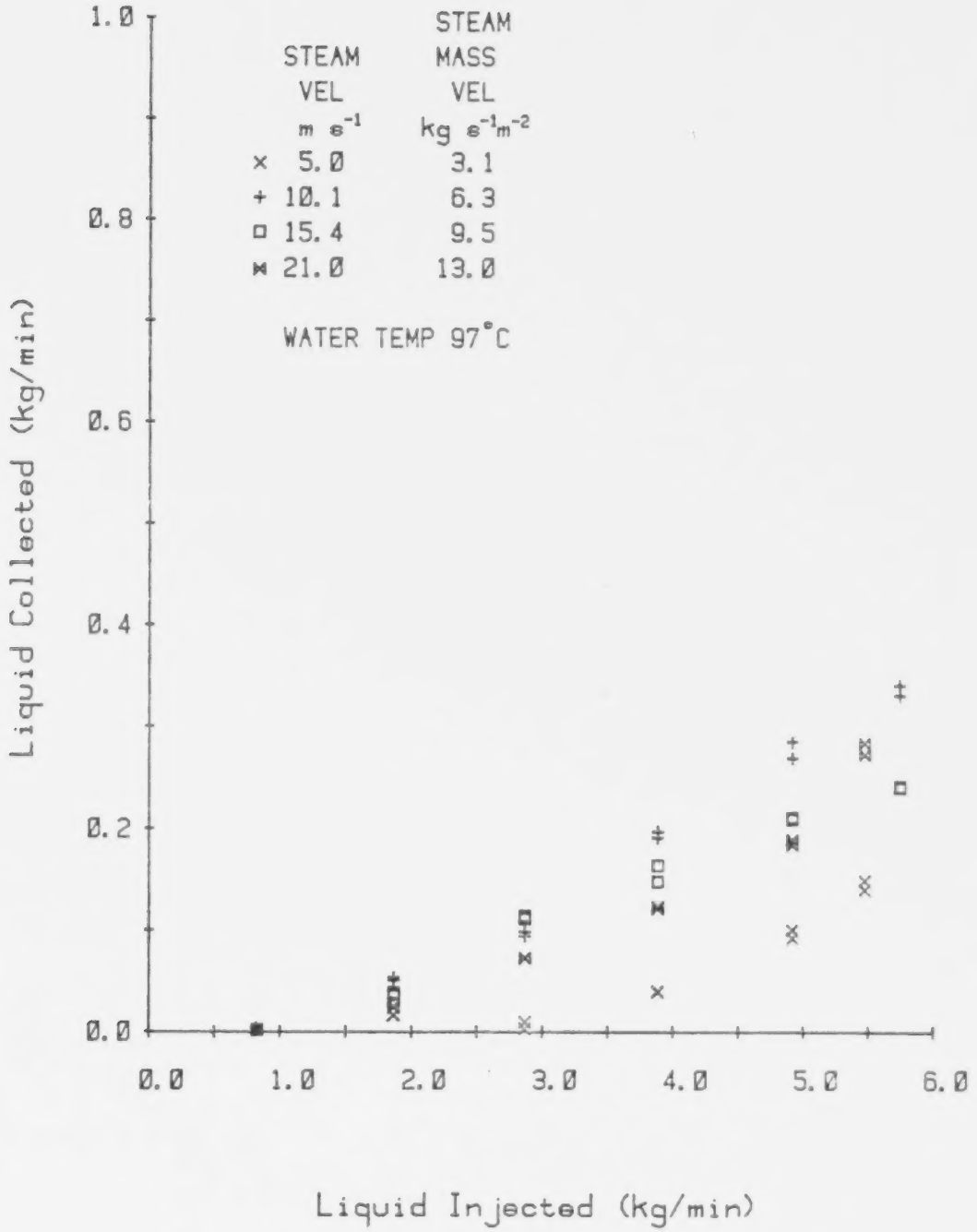


Figure 30

UPSTREAM INJECTION OF WATER:

IN STEAM, ROD 4.

Figure 31 CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 1.

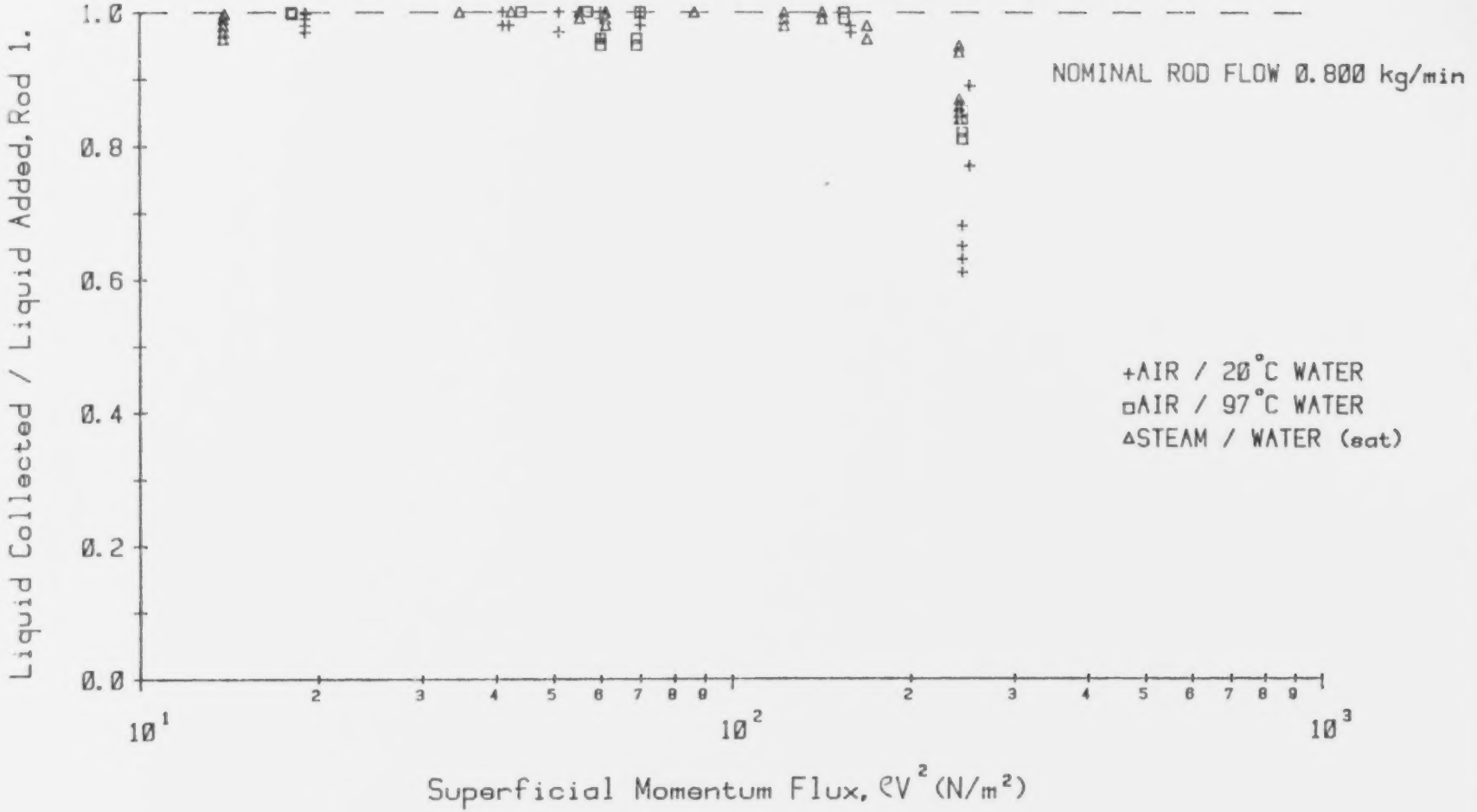


Figure 32

CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 1.

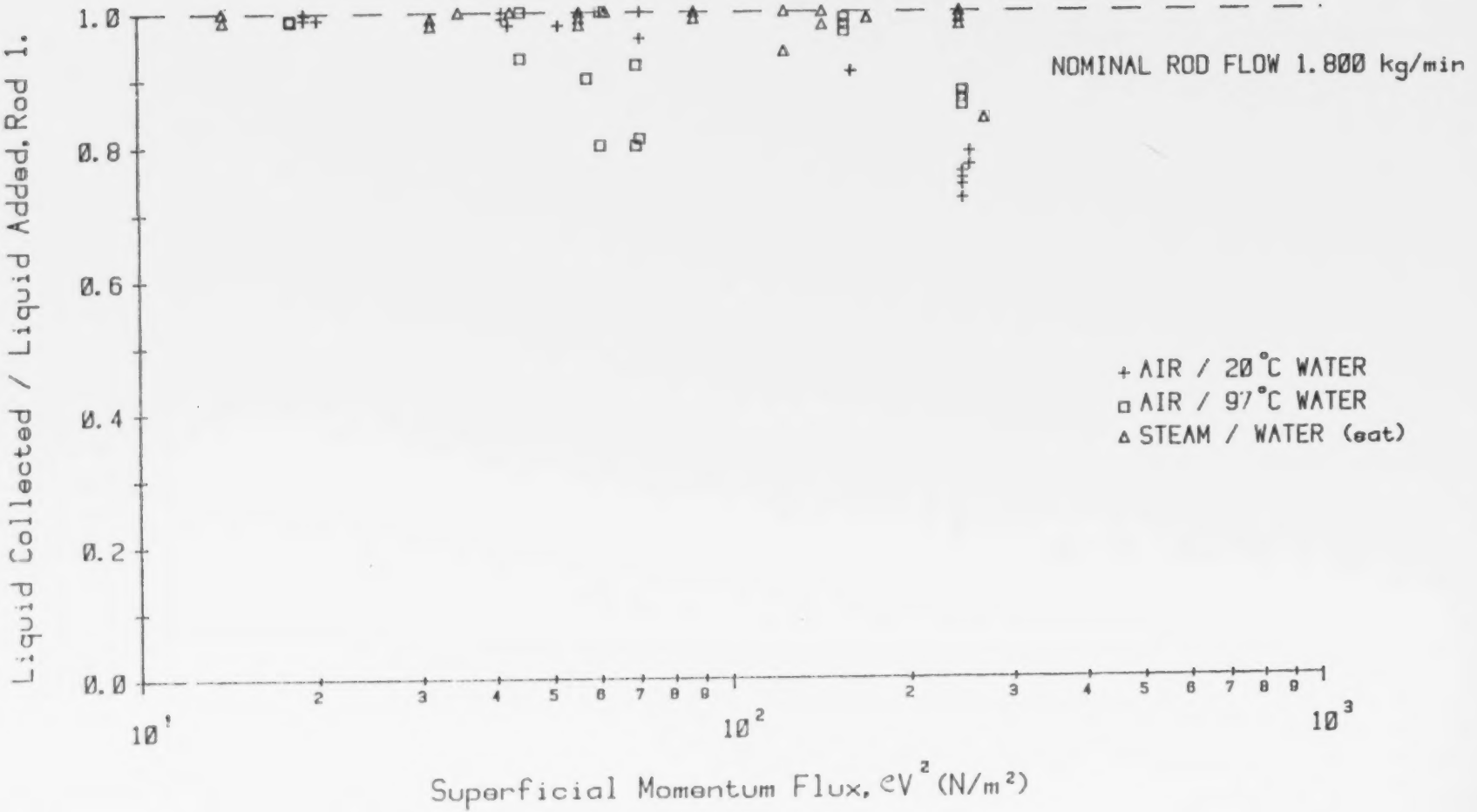


Figure 33 CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 1.

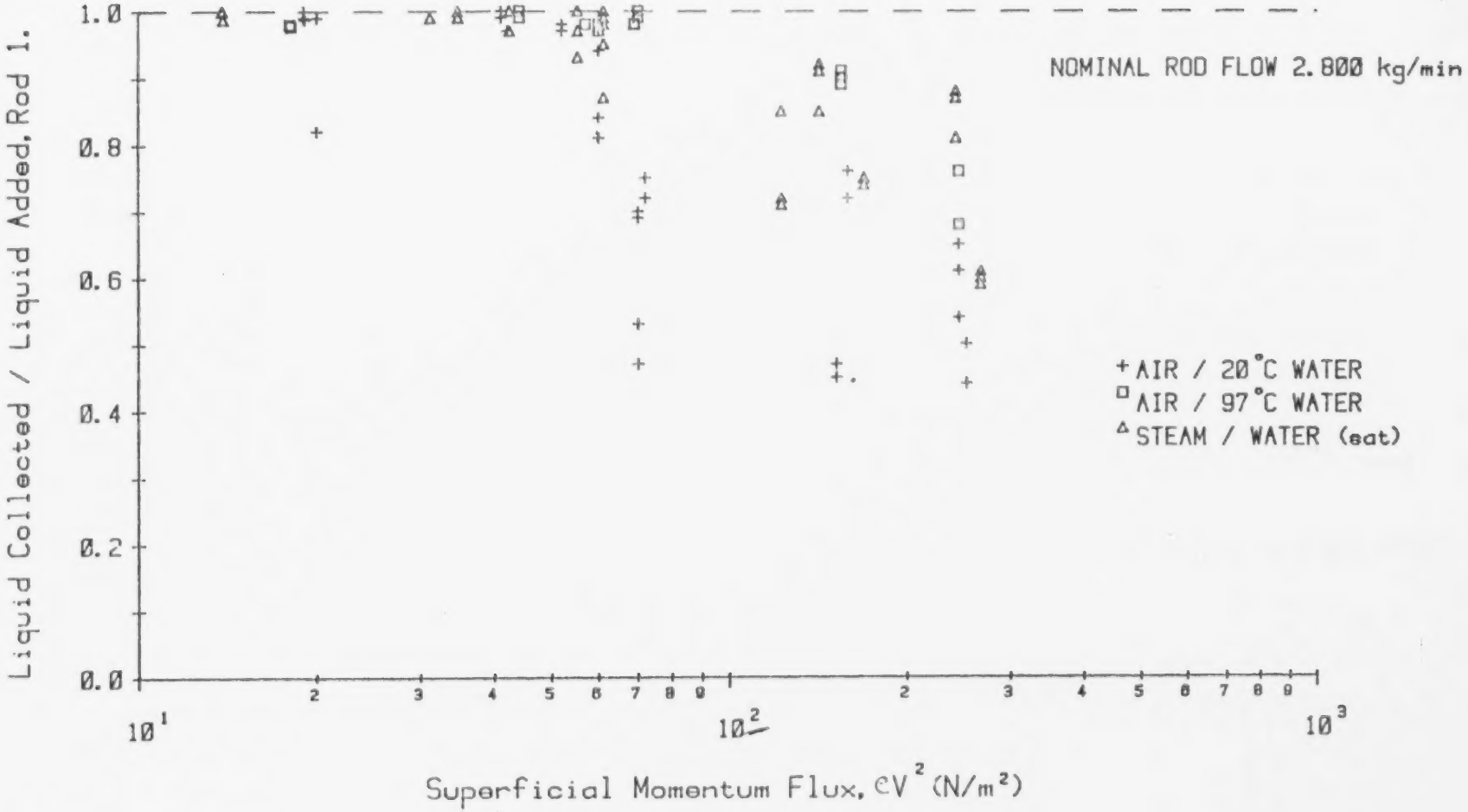


Figure 34

CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 1.

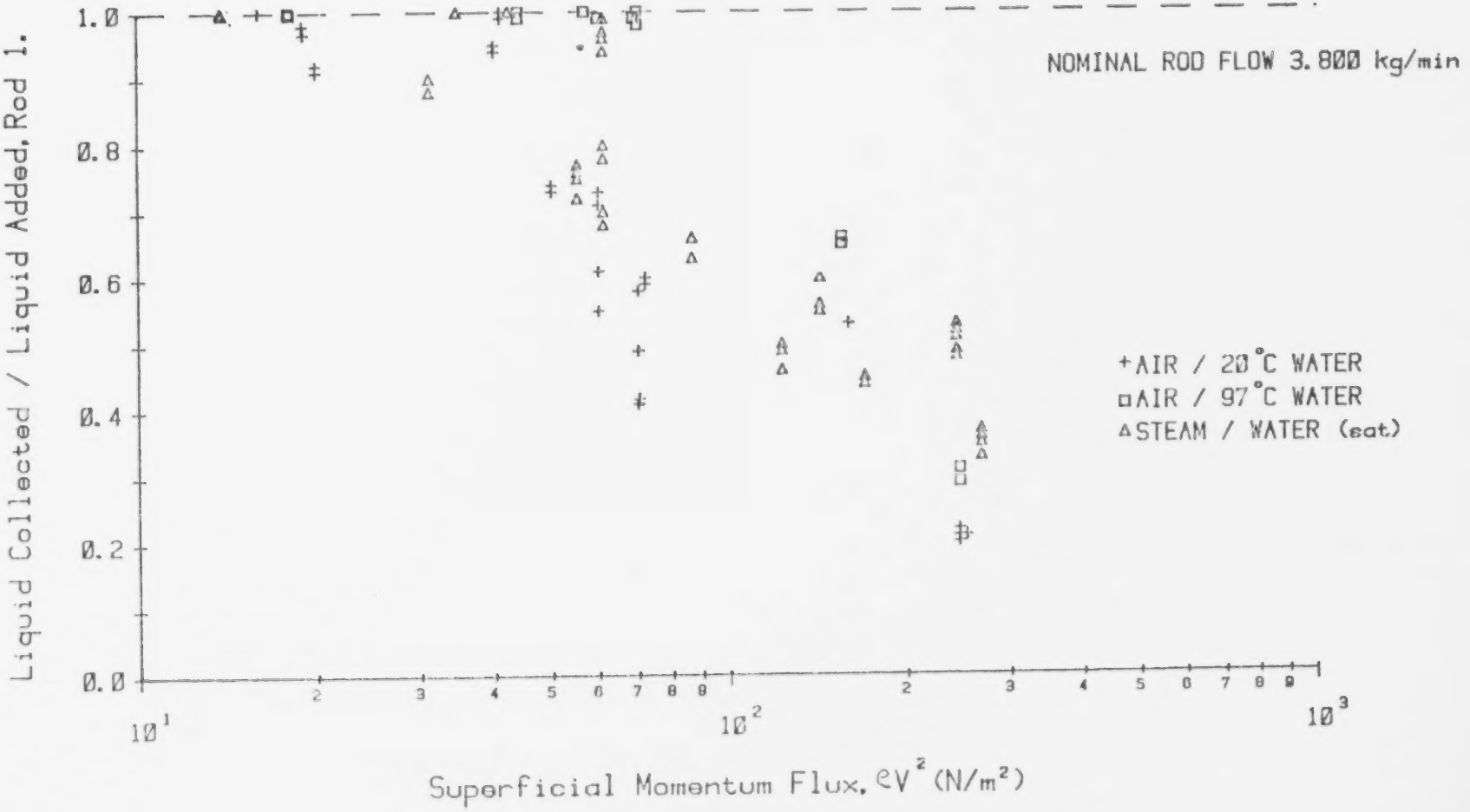


Figure 35 CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 1.

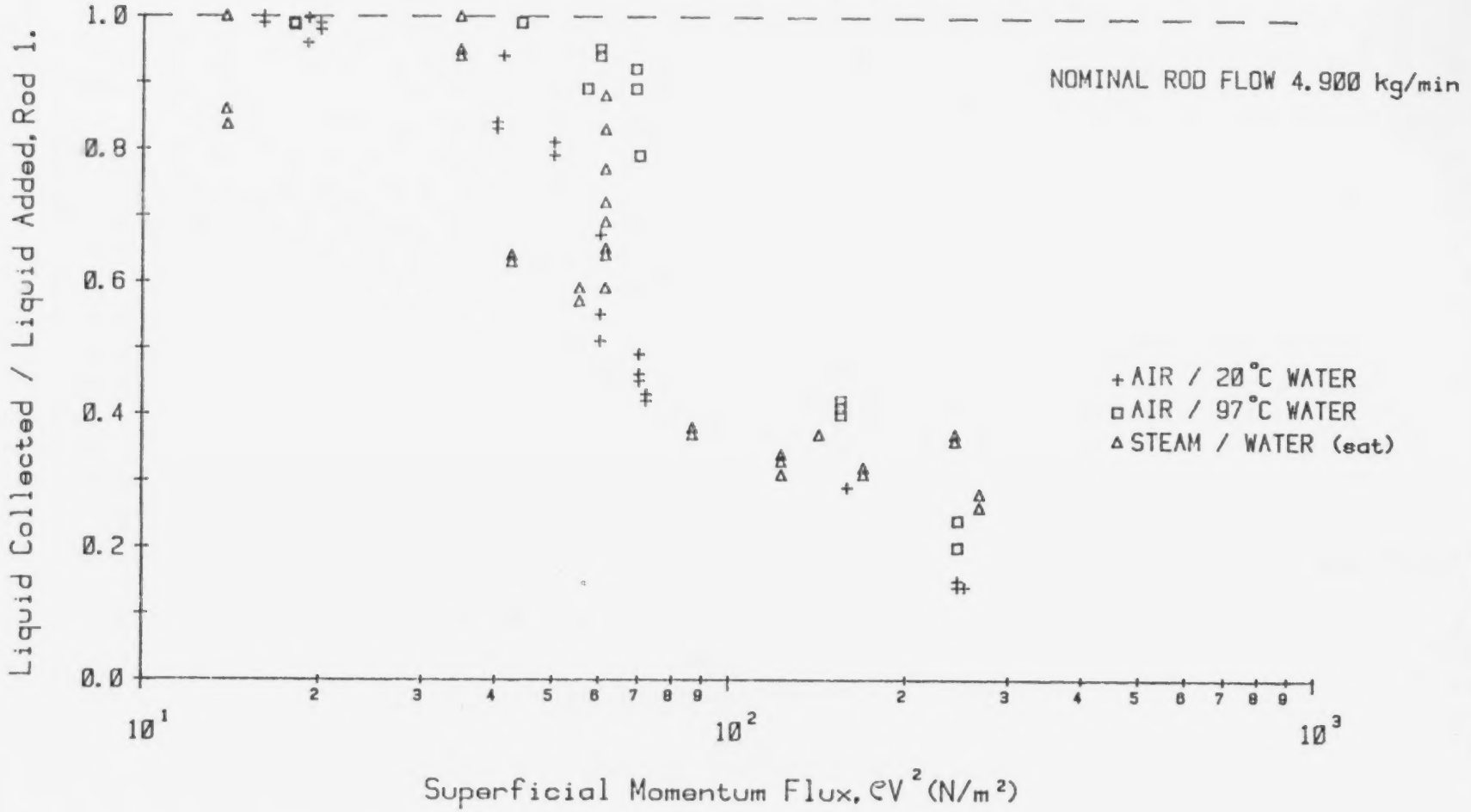


Figure 36 CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 1.

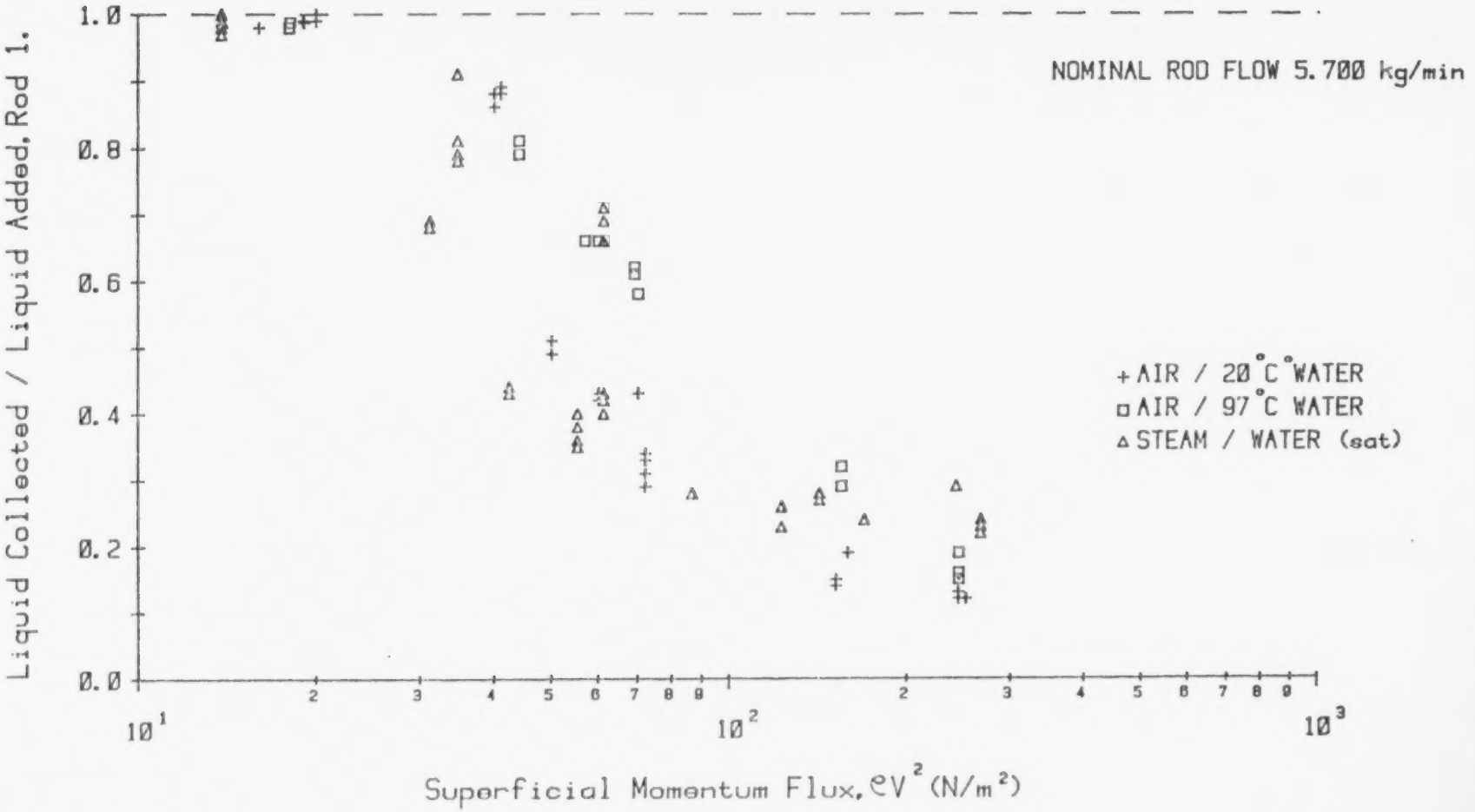


Figure 37 CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 4.

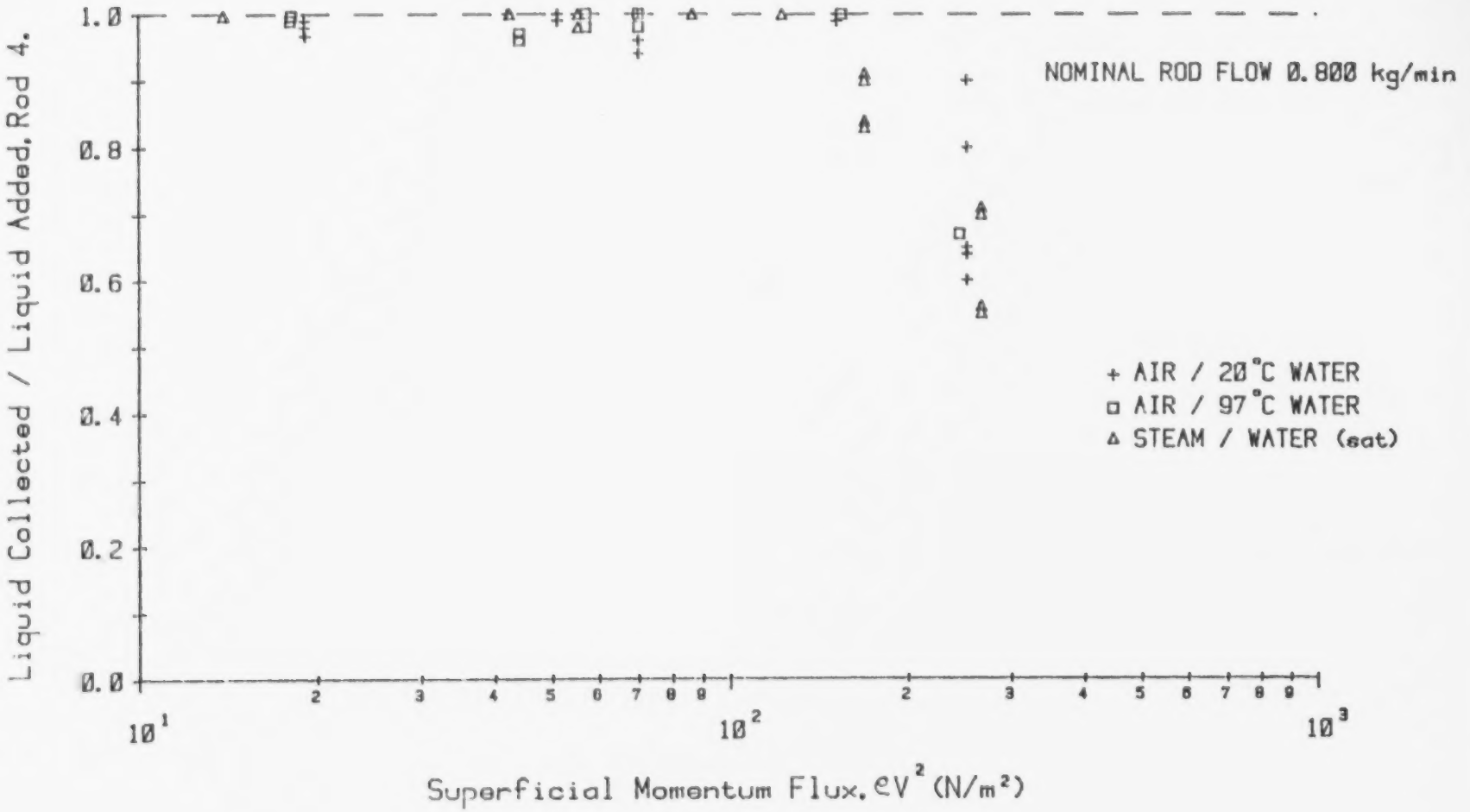


Figure 38

CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 4.

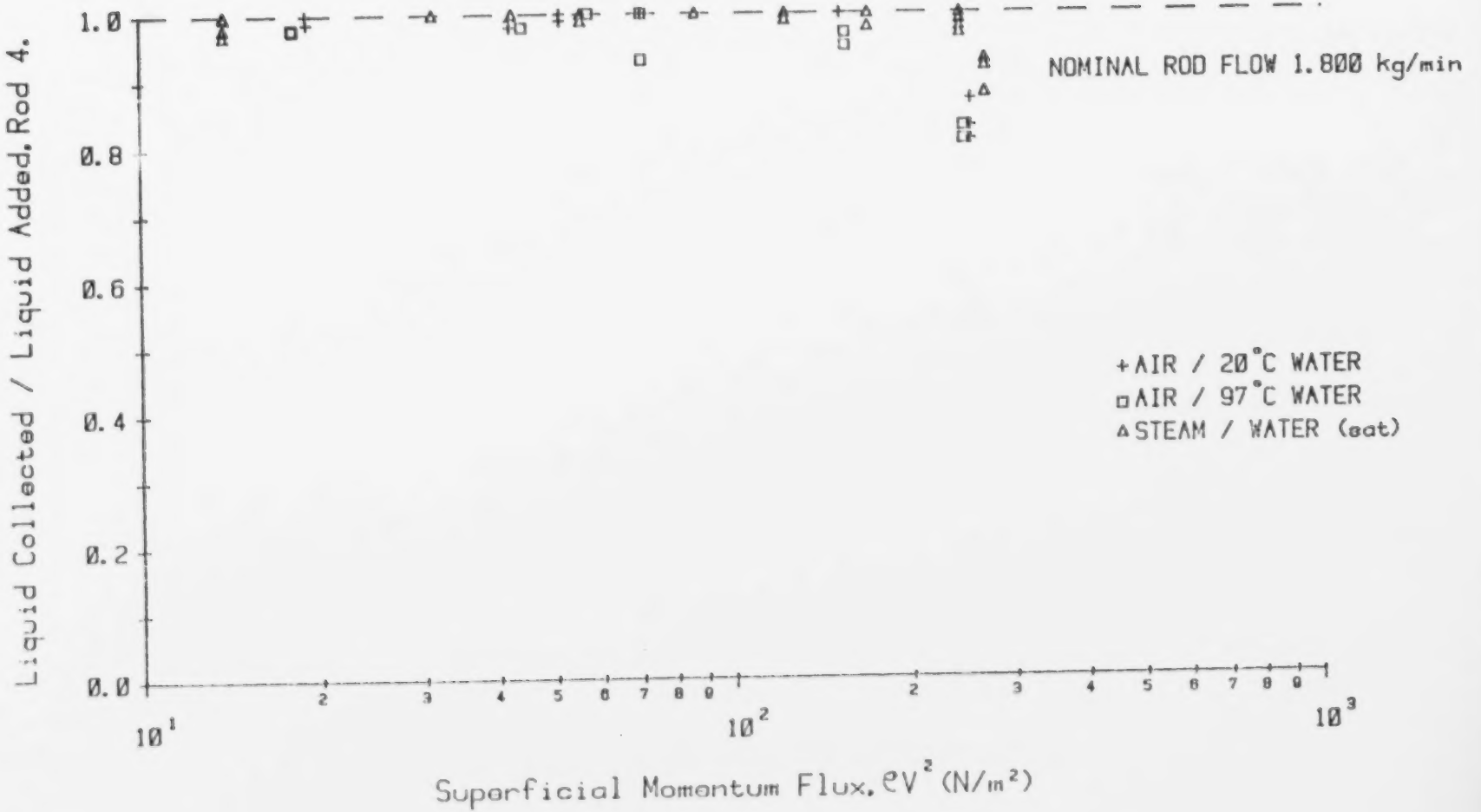


Figure 39

CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 4.

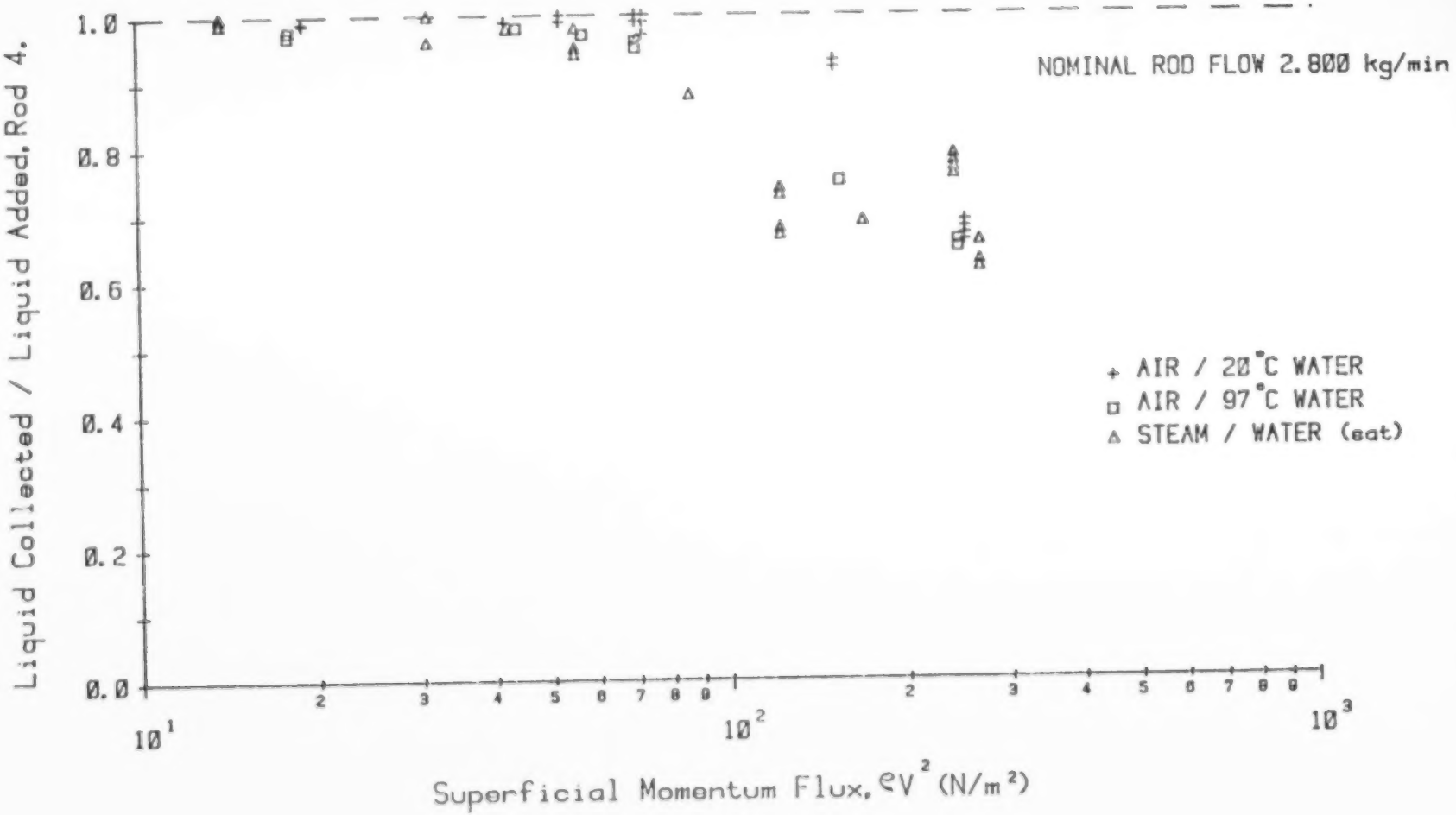


Figure 40

CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 4.

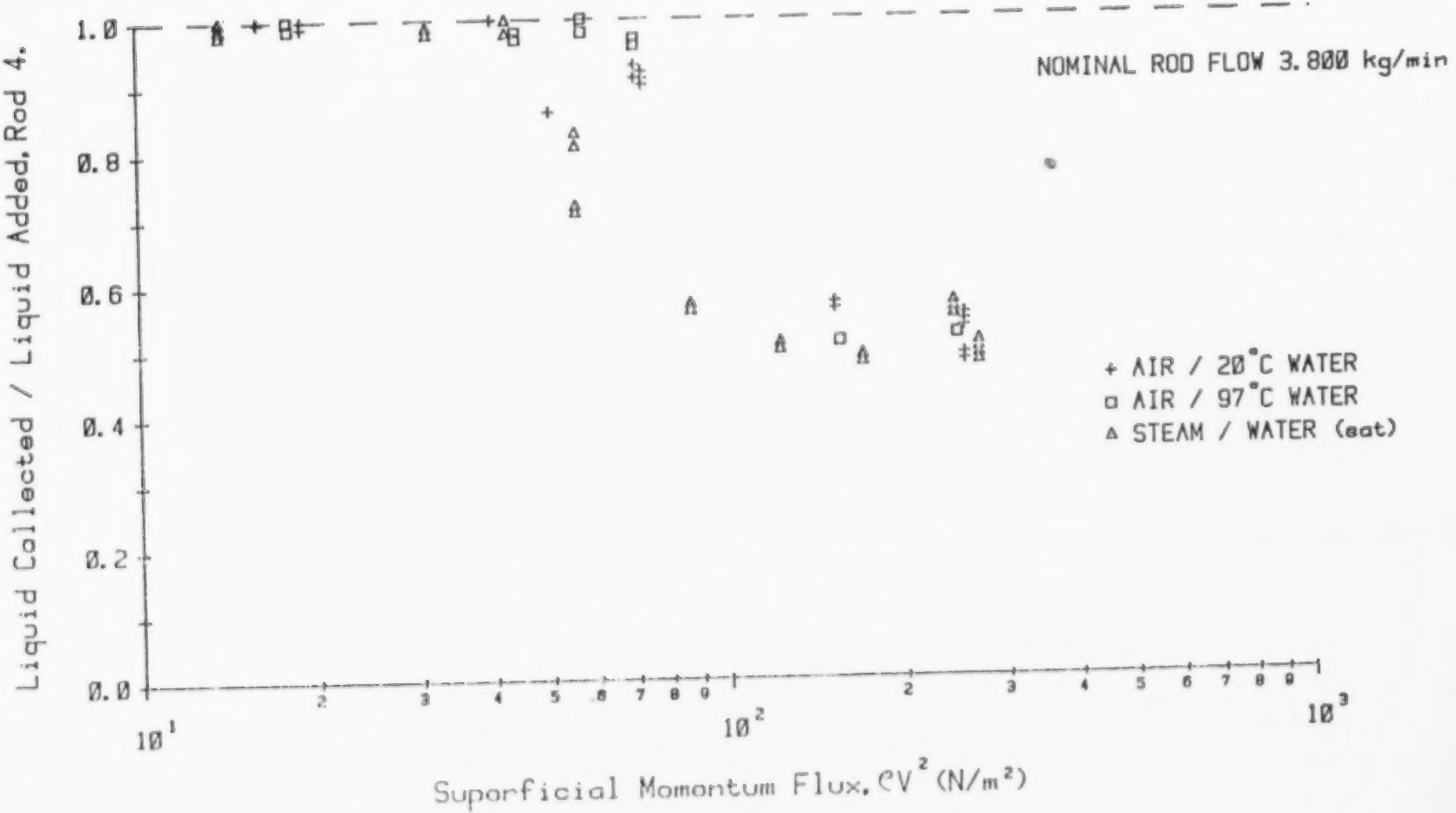


Figure 41

CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 4.

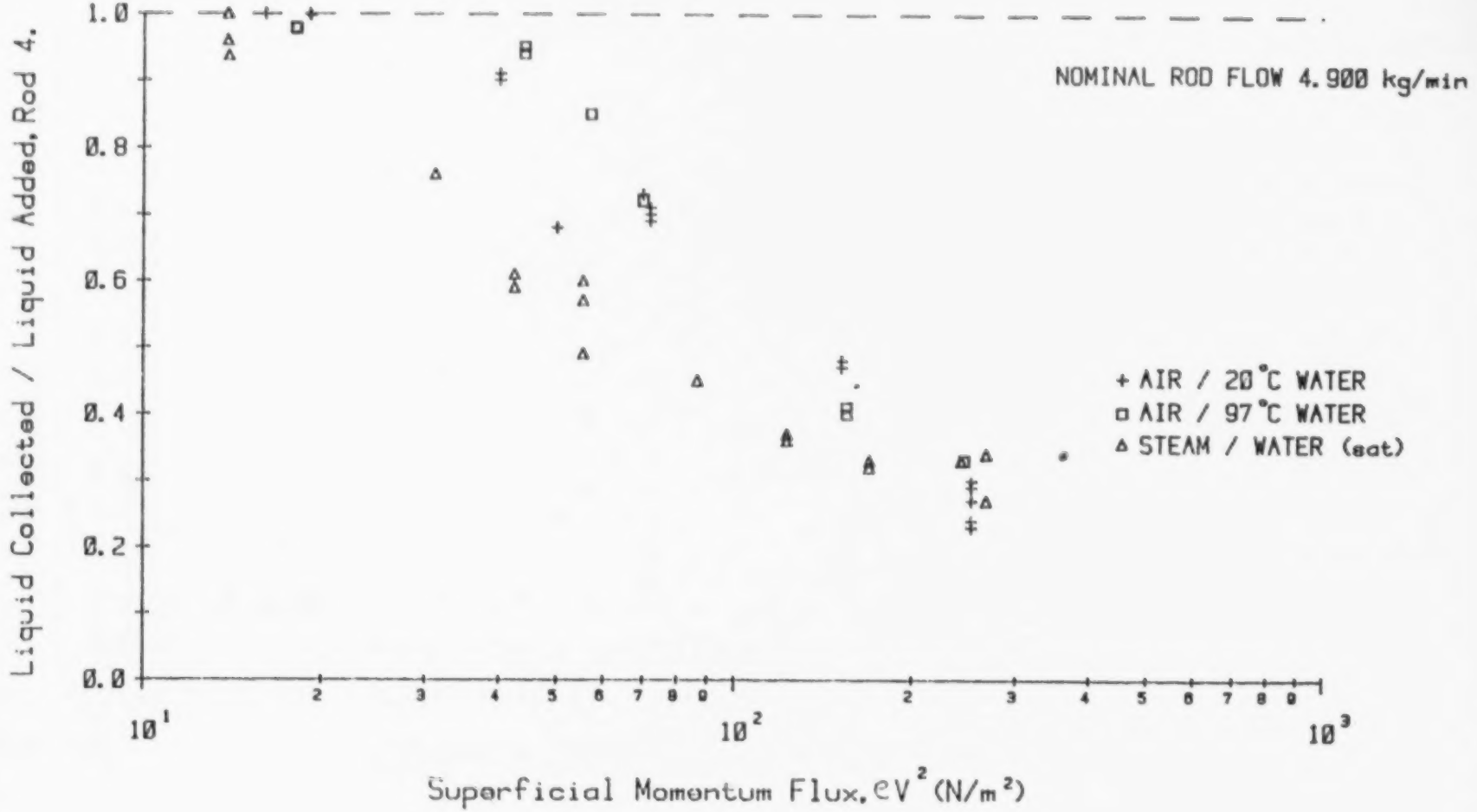


Figure 42 CORRELATION OF ENTRAINMENT WITH CROSS-FLOW MOMENTUM FLUX, ROD 4.

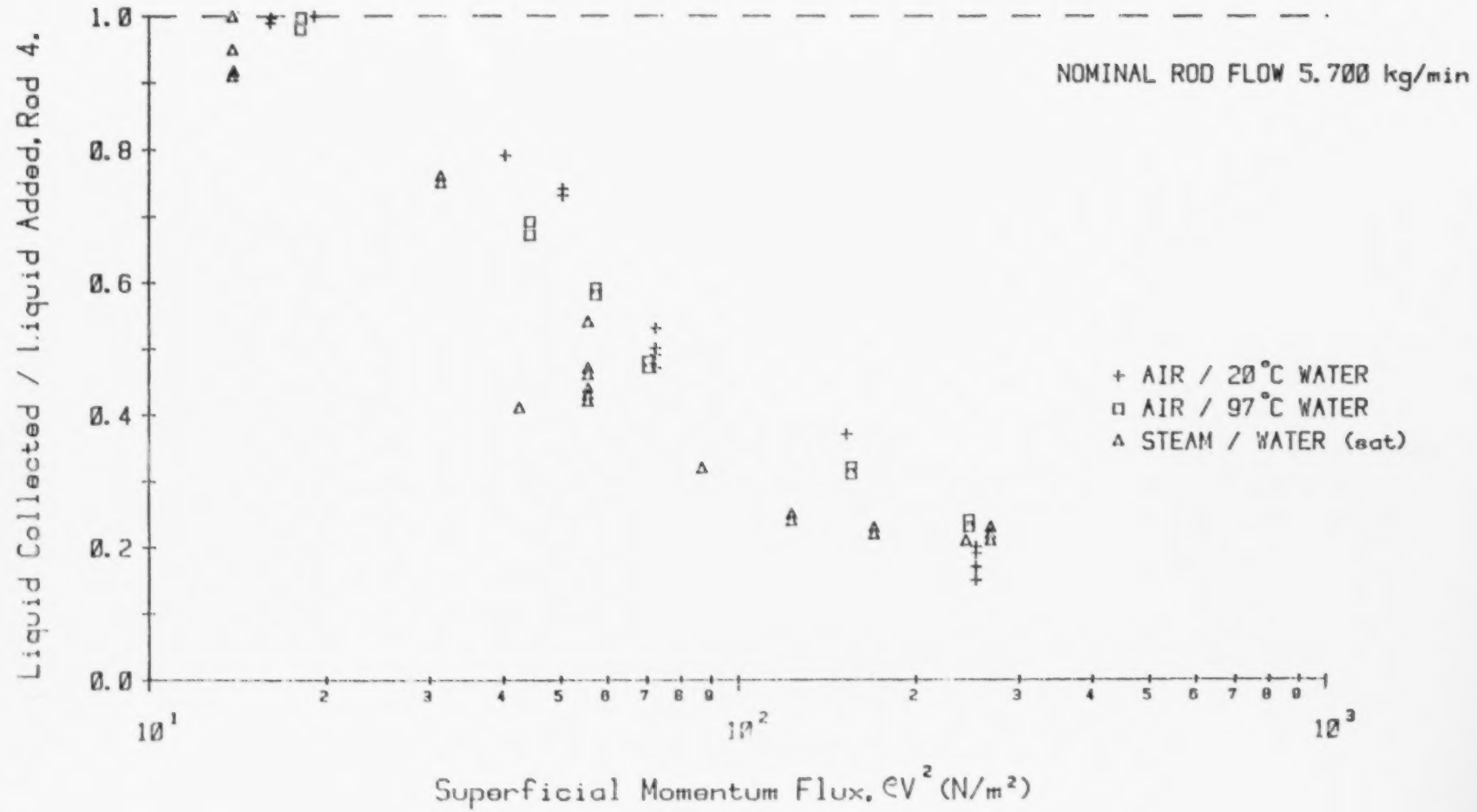
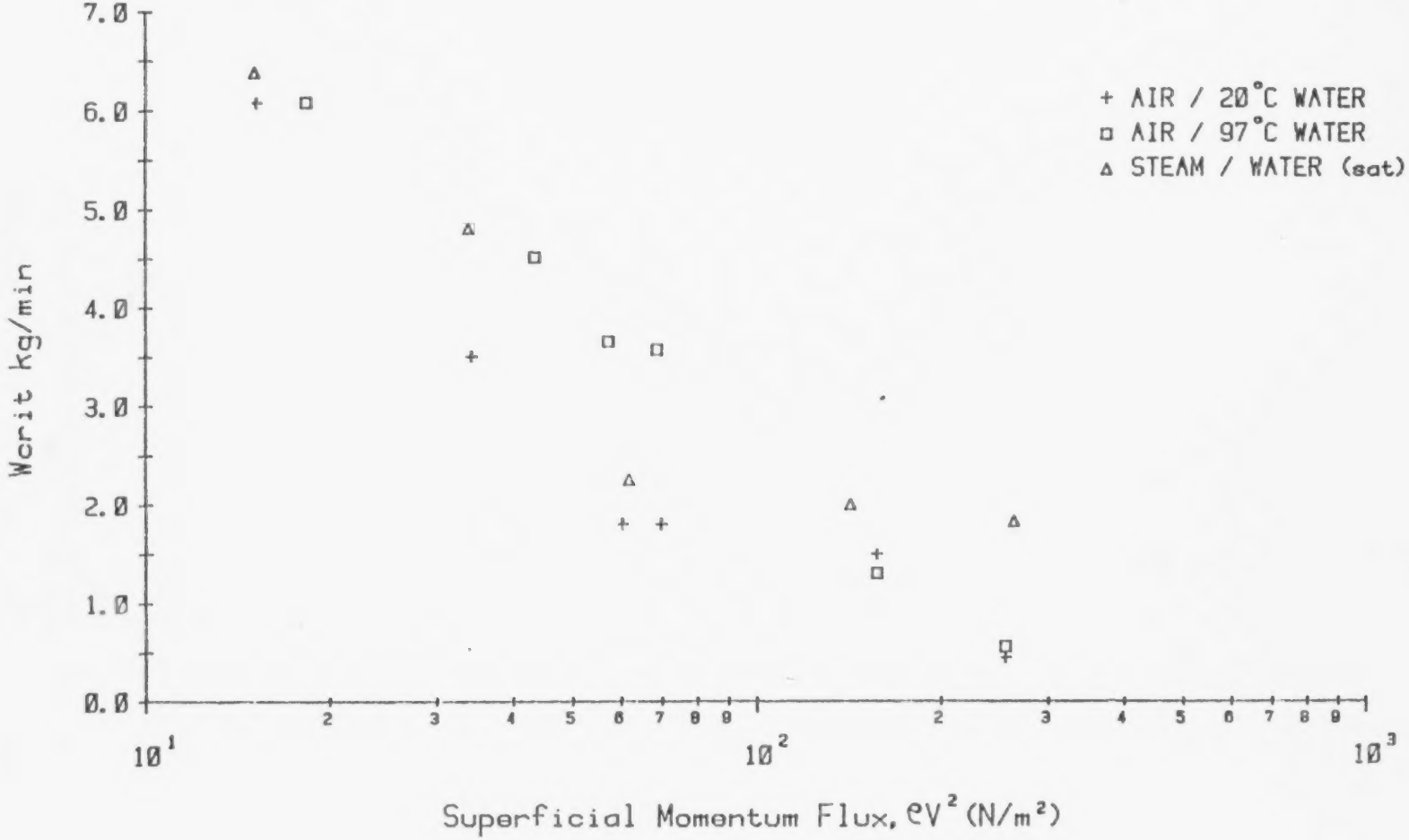


Figure 43

CORRELATION OF CRITICAL FILM FLOW WITH CROSS-FLOW MOMENTUM FLUX.



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16. ABSTRACT (200 words or less)

Air-water simulation studies of two phase steam water flow relevant to the upper plenum of a PWR during reflood situations have recently been undertaken at Harwell for the US Nuclear Regulatory Commission[1]. In order to give confidence that the simulation fluids were capable of modelling the important features of the flow in the actual system, a relatively basic comparison experiment has been carried out.

Water entrainment and deposition tests have been carried out on a pair of 2.5 cm diameter vertical rods mounted in a cross flow of steam or air in a 10.2cm x 10.2 cm tunnel.

The air and steam systems exhibited similar characteristics to one another. A 'critical' film flowrate was identified for the rods which, once reached, either by injection through the sinters or by entrainment from the main two phase stream, was not exceeded with further water addition.

The 'critical' film flowrate decreased with increase of cross flow velocity and was lower for air than steam at the same velocity.

The results from the air and steam tests were found to be reasonably well correlated on the basis of the cross flow momentum flux of the air or steam.

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Entrainment
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